Cranfield University

Dmitry Borisoglebsky

Development of frameworks for steel manufacturing planning capability improvement using discrete event simulation

School of Applied Sciences

PhD Thesis

Cranfield University

School of Applied Sciences

PhD Thesis

Academic Year 2012-2013

Dmitry Borisoglebsky

Development of frameworks for steel manufacturing planning capability improvement using discrete event simulation

Supervisors: Prof. R. Roy, Dr. E. Shehab

February 2013

This thesis is submitted in partial fulfilment of the requirements
for the degree of Doctor of Philosophy

Abstract

Customers of a steel manufacturing company now order a large number of low volume orders instead of a small number of high volume orders as they would have done just a few decades ago. The change in customer expectations has complicated production planning and scheduling within a steel manufacturing company.

The aim of this research is to improve production planning and scheduling capability in steelmaking using one of the popular simulation techniques, called discrete event simulation. In this research it is observed that there are three major areas that need attention to improve production planning and scheduling capability. First, selection of optimal schedules and plans based on throughput, production time, stock size, and other production processing criteria. Next, incorporating cost into the criteria to select the schedules and plans will make the planning more cost effective and realistic at the same time. In addition, with the increased use of discrete event simulation modelling, there is a need to improve the model development efficiency and make the process less reliant on practitioners' experience and capabilities, in order to improve the overall planning and scheduling capability. This thesis presents frameworks to address the three major areas for the capability improvement.

This research adapts a systematic approach to validation. Theoretical, realisation, and empirical parts of the research were separately validated. Real life case studies were used for validation of each proposed framework.

Discrete event simulation can improve the accuracy of production planning & scheduling and cost estimation for complex production systems. GA-based multi-objective optimisation can be successfully applied to optimisation of plans and schedules. Production planning and scheduling optimisation for some production areas provides a challenging problem to GAs. Cost estimation in the steel manufacturing company needs improvement because of the current lack of accurate costs of product families that affects quality of price management. The developed cost estimation technique is capable of providing more realistic cost for product families. The cost estimation technique would be useful for companies operating on volume-driven manufacturing processes rather than on unit-driven. Conceptual modelling needs to be improved in order to achievein model development efficiency and to make the process less reliant on practitioners' experience and capabilities. A formal information collection process can aid conceptual modelling of production systems by further development of DES models for cost estimation.

Contents

List of Figures

List of Tables

Glossary

BU	Business Unit
CS1	Case study 1
CS2	Case study 2
CS3	Case study 3
CTL	Cut-to-length
DES	Discrete Event Simulation
DEVS	Discrete EVent System Specification
DS	Dispatching area
EDD	Earliest due date
FIFO	First in first out
FMM	Fellowship in Manufacturing Management
PS	Packaging area
PPS	Production planning and scheduling
RD&T	Research Development & Technology
RTS	Road Transportation System
SLA	Service-level agreement
S&OP	Sales and Operations Planning
SPT	Shortest processing time
TOC	Theory of constraints
WIP	Work in process

The following notations are used in Chapter 6	
n_m	the number of machines in a production system
n_r	the number of resources in a production
n_p	the number of product families
k_m	index of a machine
k_r	index of a resource
k_p	index of a product family
M_{n_m}	matrix to represent machines
R_{n_r}	matrix to represent resources
P_{n_p}	matrix to represent product families
A_{n_r,n_m}	matrix to represent resource – machine relationships
B_{n_r,n_m}	matrix to represent consumption of resource in machines
D_{n_p,n_m}	matrix to represent machine – product family relationships
G_{n_m}	matrix to represent utilisation of machines
H_{n_r}	matrix to represent utilisation of resources
U_{n_r,n_m}	matrix to represent utilisation of a resource in a machine
C_{Avg}	average cost per tonne from standard costing system
C_{k_r}	average cost of a resource from a standard costing system
β_{k_r}	percentage of the average cost per tonne from a standard costing system, which is related to a average cost of a resource per tonne
W_{n_p}	matrix to store the weights of product families have been processed
w_{k_p}	the weight of a product family has been processed
Y_{n_p,n_r}	matrix to parts of resource utilisation by product family
z_{k_p,k_r}	part of resource utilisation by product family
Z_{n_p,n_r}	part of resource utilisation by product family considering throughput
z_{k_p,k_r}	part of resource utlisation by product family considering throughput
S_{n_p,n_r}	matrix to store overall estimated cost
s_{k_p,k_r}	resource's part of overall estimated cost per product family
s_{k_p}	overall estimated cost of a product family
V_{n_p}	matrix to store costs per tonne for each product family
v_{k_p}	cost per tonne of a product family

Chapter 1

Introduction

Customers of a steel manufacturing company now order a large number of low volume orders instead of a small number of high volume orders as they would have done just a few decades ago. The production systems in Tata Steel Europe, the major sponsor of this research, were originally designed for a small number of high volume orders. The change in customer expectations has complicated production planning and scheduling within the steelmaking company. In addition, with the current marketing trend for customisation, production planning and operational management teams are facing regular challenges.

The aim of this research is to improve production planning and scheduling capability in steelmaking using one of the popular simulation techniques, called discrete event simulation (DES). In this research it is observed that there are three major areas that need attention to improve production planning and scheduling capability. First, selection of optimal schedules and plans based on throughput, production time, stock size, and other production processing criteria. Next, incorporating cost into the criteria to select the schedules and plans will make the planning more cost effective and realistic at the same time. In addition, with the increased use of the DES technique, there is a need to improve the model development efficiency and make the process less reliant on practitioners' experience and capabilities, in order to improve the overall planning and scheduling capability. This thesis presents frameworks to address the three major areas for the capability improvement.

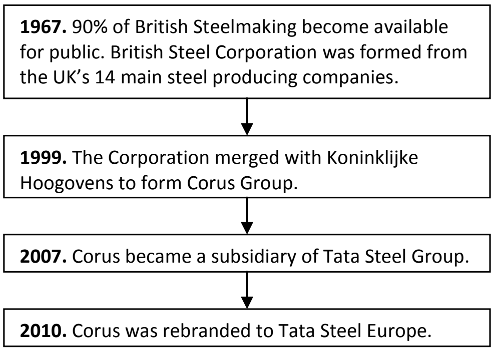


Figure 1.1: Key events of Tata Steel Europe's history.

The focus on DES modelling is supported by the following rationale. The author intended to use one approach for modelling of production areas of a big steel manufacturing company. These production areas are characterised by the following criteria: process-oriented production processes, top-down modelling, details of production elements, flow of entities through a production system, modelling on operational level, dynamic and stochastic nature. Discrete event simulation satisfy these criteria [1, 2, 3].

1.1 Tata Steel Europe

The major sponsor of this research, Tata Steel Europe, which is a part of a larger company Tata Steel Group, which by itself, is a part of Tata Group. Tata Steel Europe [4] is the second largest steel manufacturing company in Europe, with its main steelmaking operations in the UK and the Netherlands. This company was formerly known as Corus Group, which was formed via the merger of British Steel and Koninklijke Hoogovens on 6 October 1999. They chain of key events, mainly for the British side, is visualised in Figure 1.1.

Tata Steel Europe, a big steel manufacturing company, has a number of production business units (BU) mainly located in the UK and the Netherlands providing numerous products for different industries. Most of the BU specialise in one group of products, such as steel bars, coils, or tubes with different physical and geometrical properties. The products in the given example are produced in different BU and form a chain of

Figure 1.2: Brief introduction to the company's geographic of production facilities.

production. With the given collaboration, BU are managed separately from each other and have their own production specifics.

Tata Steel Europe produces a variety of steel products. The production facilities are located in the UK, the Netherlands, Germany, and France. The major locations are shown in Figure 1.2; Google Earth, and information from the company's website [4] were used in the development of this figure. While the corporation provides steel products and services, this figure contains the locations of production facilities only; the rest: consulting, distribution, and sales networks are excluded from Figure 1.2.

Providing different products and services, these production locations serve a variety of industries. Figure 1.3 contains a list of products that are utilised by these industries.

1.2 Steel making

Steel making is a general term for steel manufacturing production processing, starting from mining and finishing with some basic products that can be found in any store (nails, screws, tubes, etc). Scrap yards and the machinery used in secondary steel making is also a part of steel making. The Engineering Employers Federation (EEF), an organisation that represents manufacturing in UK, provides educational materials about steel making [5]. Figure 1.4 shows the major processes of steel making; the original visualisation from the website [5] provides a better insight into the process.

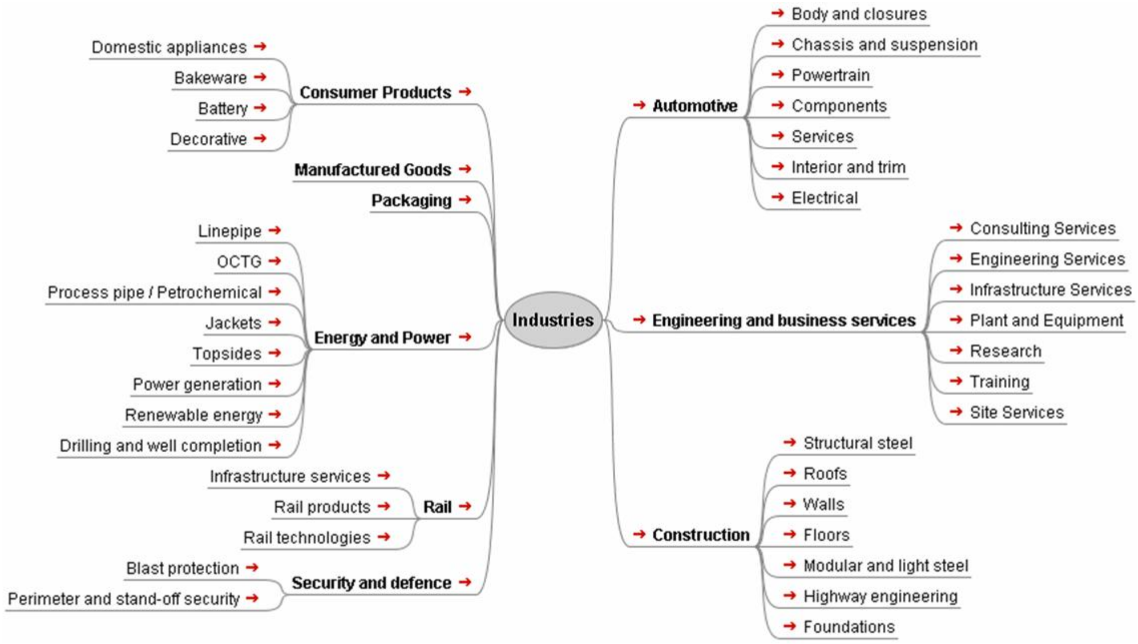


Figure 1.3: Products of Tata Steel Europe [4].

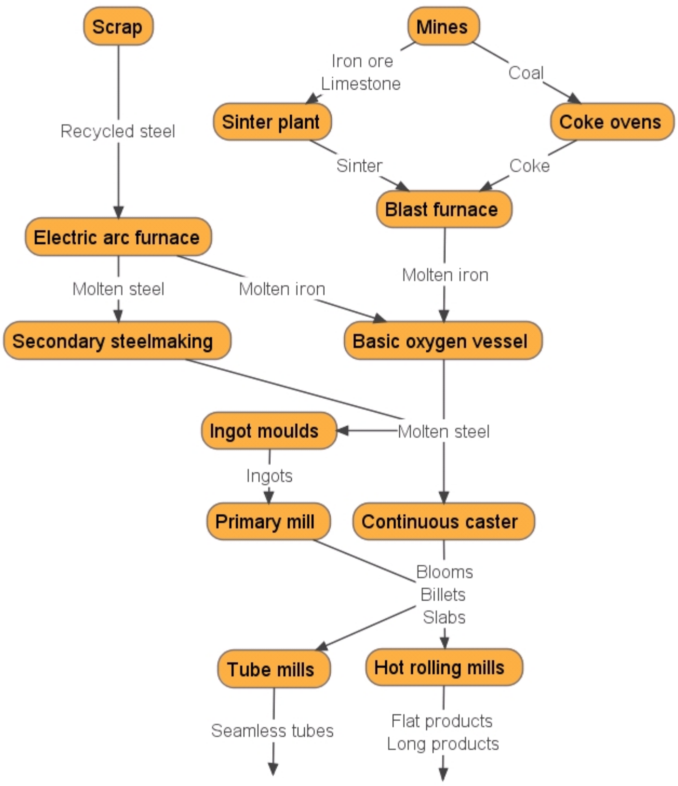


Figure 1.4: Generic steel making process, re-drawn from [5].

1.3 Simulation modelling in Tata Steel Europe

High-volume production using expensive and big machines that form a complex production system is the nature of steel manufacturing. These production systems are too big for physical modelling and too complex for comprehensive mental modelling, which leaves computer modelling as the only feasible option. The complexity of steel manufacturing production systems arises from dynamic and stochastic interactions between a large number of machines, products, transporters, people, etc. There is just a theoretical chance of accurately modelling a complex production system using linear modelling. On the contrary, discrete event simulation, agent based simulation, and system dynamics are designed for dynamic and stochastic environments. Due to the characteristics of these computer simulation modelling techniques and the experience of Tata Steel Europe employees, discrete event simulation is selected as a simulation modelling technique for this research.

A common approach to computer modelling of complex production systems having dynamic and stochastic behaviour is discrete event simulation [1]. Discrete event simulation is used in many industries to solve a broad variety of problems. Practitioners have developed a methodology for DES modelling projects. Simulation modelling projects begin with 1) problem formulation, followed by 2) the development of an information (conceptual) model and data collection, 3) implementation of a model using a programming language or modelling tool, 4) verification and validation, 5) planning and running experiments, 6) analysis and writing results, and 7) taking action.

Tata Steel Europe Research, Development & Technology (RD&T) business unit has been developing DES models for production business units over the last decade. According to the objectives of the simulation modelling projects (see Appendix A), DES was mostly used to study the capabilities of production systems or impact of new products and production strategies to the existing system. Some of the projects involved manual experiments with production plans and schedules. This thesis provides a solution for an automatic generation of a set of nearly optimal production plans and schedules.

Previous, current, and future modelling projects may be re-used to serve the company's need for accurate cost estimation. In this case, it is beneficial for RD&T to know what information to collect for further development of DES models capable of cost estimation; information collection is related to the early stages of the simulation-modelling project. According to the company's simulation engineers, early stages of DES modelling sometimes take up to fifty percent of the lead-time of a project. Robinson [6] commented that this area lacks research and studied [7, 8] conceptual modelling on a generic level. This thesis provides a solution that is specific to simulation modelling of production processes and cost estimation.

1.4 Production planning and scheduling

Production plans and schedules are closely interrelated concepts. Planning is a definition of product mixes and quantities a company is expecting to produce, while scheduling is focused on a time-sequenced introduction of products into a production system that efficiently supports the plan.

Tata Steel Europe is a company with many production facilities. Each of these facilities was an individual company (mostly focused at a specific type of steel product, such as steel bars, coils, and tubes), prior to the integration into one company. This affects the company policies regarding production planning; each of the production facilities has its own production planning and scheduling system. Obviously, while there are differences due to production specifics and historical preferences, there are also general similarities shared by mass production companies; sales fill an order book, production fulfils these orders, and dispatching sends these orders to customers.

Some production facilities of Tata Steel Europe make individual attempts to improve their production planning and scheduling systems. In particular, their interest and need are big enough to trigger the improvement projects. Developed and validated DES models provide accurate and trustworthy results; therefore, DES models may be used for production planning and scheduling, and some of the models already served this purpose (see Appendix A).

This does not mean that PPS activities in Tata Steel Europe are limited to DES. DES is merely a technique that allows modelling of complex stochastic and dynamic systems, which makes it useful for the production facilities. In such occasions, however, DES models were used to run manual experiments, and DES modelling have a higher potential if combined with an automatic generator and comparison of production plans or schedules, ideally with an approach that is aimed to optimise production plans or schedules by a number of relevant criteria.

Some of the optimisation approaches are more compatible with DES modelling than others. Classical optimisation approaches are not suitable, and on the contrary, evolutionary algorithms are suitable for use with DES due to the following characteristics [1, 9, 10, 11]: DES models are as unique as the respective production processes, have complex behaviour and noisy output, often incorrect inverse problems and discontinuous parameter change, noncompact search space and many extreme performance measures. As explained in Section 2.2.3, evolutionary algorithms were narrowed down to *genetic algorithms* (GA).

DES & GA were previously used to improve the efficiency of production systems. Andersson et al. [12] have mentioned direct and indirect methods to the optimisation of production schedules. This binary classification might be extended on the basis of chromosome's content. A five-category classification was developed and described in Section 2.2.4.

Some of these approaches are not suitable for the optimisation of production plans or schedules of a steel manufacturing company. Modifications of a production site's layout are generally an inappropriate method for steel manufacturing due to massive and expensive equipment. The application of the optimised production parameters and dispatching rules would require a significant change in manufacturing procedures and personal training to be a generic solution for a multi-factory company, yet useful for individual singular projects. On the other hand, time-sequenced introduction of products is a generic method, which requires minor changes in operation management, production planning, and sales departments.

1.5 Cost estimation

This mass production company is managed with standards, which define various aspects of production management, accounting, *etc*. This company uses standard costing for the estimation of production costs, *i.e.* the production cost of one production area is measured in GBP per one unit of throughput, a tonne of steel. For example £100 per tonne on average for three projects, while the real costs are different: £60 for the first, £80 for the second, and £160 per tonne for the third project. This difference in real costs is explained as follows. Different products, even though they are going through one production area, get assigned to the same costs on paper; however, one product would skip processing by most of the machines and another would be processed by all of them, therefore, accumulating more costs.

In addition, the current marketing trend is showing further customisation of products for customers. For Tata Steel Europe that means the change from a small number of high volume orders a few decades ago to a greater number of low volume orders now; this change makes a standard costing approach less feasible to use. As the result, questions such as '*What is the real production cost?*' remain unanswered, as the finance departments cannot distinguish between profitable and unprofitable products, which leads to vague understanding of sales qualities, and sales departments are unable to distinguish between them due to vague progress reports.

This thesis provides a classification of cost estimation techniques and a novel cost estimation technique designed for the environment of Tata Steel Europe. This product family based cost estimation technique is capable of accurately estimating relative costs of products. It utilises information from a simulation model of a production area and standard costing system, therefore, does not contradict the current costing practices of this big company, yet provides surprising differences in production costs.

1.6 Summary and knowledge contribution

This research project was initiated on the basis of agreement between Tata Steel Europe, Cranfield University, and Engineering and Physical Sciences Research Council

(EPSRC). A research proposal was written for funding later provided by Tata Steel Europe and EPSRC. The author of this thesis was selected as a researcher for this project. The company provided background information and requirements for industrial deliverables. Responsibilities of the author included: validation of background information, development of industrial deliverables, and the formulation and development of academic deliverables.

The background of this research is summarised in the following statements: 1) Tata Steel Europe extensively uses standards for operations management, 2) the production systems are complex and 3) the production systems are not designed for the current business conditions.

This background leads to a number of problems. The management system based on standards does not support cost differentiation between products, therefore, it is impossible to distinguish between profitable and unprofitable products, orders, and customers. A combination of the current planning practices, complex production systems and the change in marketing trend leads to regular challenges for planning teams to deliver production plans for complex production system.

This background also limits methods which might be used for solving these challenges. In particular, due to the complexity of production system, discrete event simulation modelling is proposed for both identification of production costs and production planning. However, discrete event simulation modelling introduces an additional challenge, which is related to a solid part of a project's lead time. Up to 50% is taken by conceptual modelling and data collection; a process of information collection is suggested as a solution for this challenge.

The following knowledge contributions were provided as the result of this research: i) an information collection tool for further development of discrete event simulation models that are capable of cost estimation, ii) a classification of cost estimation techniques for systematic research in this area, iii) product family based cost estimation technique, iv) a concept of production planning optimisation was designed and compared with the previously used production scheduling optimisation.

1.7 Thesis structure

This thesis contains of eight chapters forming three groups. Definition of the research topic and methods is formed from first three chapters. Chapters from 4 to 7 are fulfilling research objectives. The final chapter concludes this research. Each chapter is introduced separately.

Chapter 1. Introduction: introduces the purpose of this research as having the capability to improve production planning using discrete event simulation modelling. Discrete event simulation modelling is capable of representing complex manufacturing systems, and production planning is one of few approaches for performance improvement of systems with expensive and very big equipment.

Chapter 2. Literature review: familiarises us with the concepts that are related to the topics of this research namely, production planning and scheduling, optimisation techniques, production cost estimation, and discrete event simulation modelling. Research gaps, that support the proposed industrial objectives, are defined at the end of this chapter.

Chapter 3. Research aim and methodology: defines the aim and objectives of this research. Analysis of the impact of the scope to the objectivity of this research. Research strategy and research methods followed by the overall research process are also defined in this chapter.

Chapter 4. Current situation: is presented in a form of the projects having the author as a participant observer. This list is followed by the important issues regarding production planning, costing, and discrete event simulation at Tata Steel Europe. This chapter is finalised with the summary that combines the most important observations into one picture.

Chapter 5. Optimisation of production plans and schedules describes one of the three sub-projects. This part of the research is focused on optimisation of both production plans and schedules using time-sequenced introduction of products as a GA chromosome that is evaluated in a DES model of production system. This provides both generic and accurate solution for production planning.

Chapter 6. Cost estimation is the second sub-project, it is focused on cost estimation using DES models. Direct and reversed approaches for cost estimation were identified; however, due to the novelty and industrial importance, this chapter is focused on the reversed, product family based cost estimation technique. A proposed classification of cost estimation techniques is also described in this chapter.

Chapter 7. Information collection is the final, third sub-project, it is focused on a process of information collection for further development of discrete event simulation models of production systems that are capable of accurate cost estimation.

Chapter 8. Discussions, conclusions, and future work. This chapter finalises the thesis with the discussion on the research results, i.e. key observations in the company, research methodology, as well as research contributions and areas for future research regarding each sub-project.

Chapter 2

Literature review

2.1 Introduction

The literature review familiarises the researcher with i) relevant concepts regarding relevant disciplines, ii) methods utilised within these disciplines, iii) current research trends. It also allows the researcher to define the research gaps.

This multi-disciplinary research project requires a literature review on both the disciplines and interconnections between them. The disciplines are loosely categorised into 'functional' and 'supporting' groups. The 'functional' group is reserved to the disciplines that are directly related to this project; production planning & scheduling and cost estimation form this group. The 'supporting' group is reserved for the disciplines that add to the functional disciplines; optimisation, which is narrowed down to genetic algorithms, and discrete event simulation modelling form this group.

Interconnections between the disciplines directly serve the solutions, production planning & scheduling using DES models as fitness functions of GA, cost estimation using DES modelling, and an information collection process for further development of DES models capable of cost estimation.

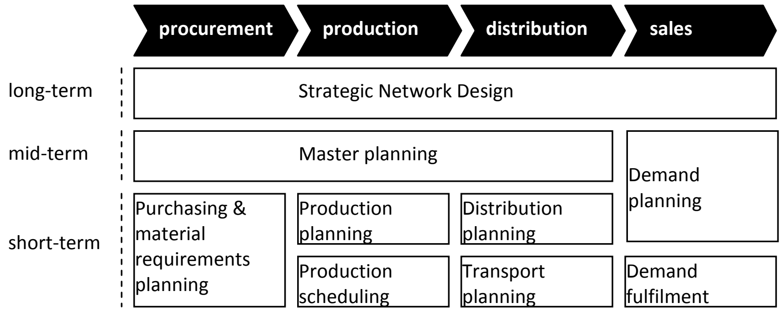


Figure 2.1: Supply chain planning matrix, re-drawn from [13, 14].

2.2 Optimisation of production plans and schedules

2.2.1 Production planning and scheduling

Planning is used by different departments on different levels of a company; with Figure 2.1 Meyr, Wagner and Rohde [13] show a structure for planning tasks. Maravelias and Sung [14] state that *'short-term planning is carried out on a daily or weekly basis to determine the assignment of tasks to units and the sequencing of tasks in each unit. At the production level, short-term planning is referred to as scheduling.'* Production plans and schedules are closely interrelated concepts [15]: the **plan** is a definition of product mixes and quantities a company is expecting to produce, while the **schedule** represents a time-sequenced introduction of products into a production system that efficiently supports a plan.

As production planning and scheduling are important concepts of operations management, a wide variety of methods were developed to support these activities. A classification of scheduling problems and algorithms used for production scheduling with the number of reviewed papers are listed in Figure 2.2.

2.2.2 Production planning and scheduling in steel manufacturing

Table 2.1 provides an overview of production planning and scheduling in the steel manufacturing domain from the year 2000 to 2010. While most of the papers are simply cited with the authors, problem areas and scheduling methods, two papers; Tang et al.

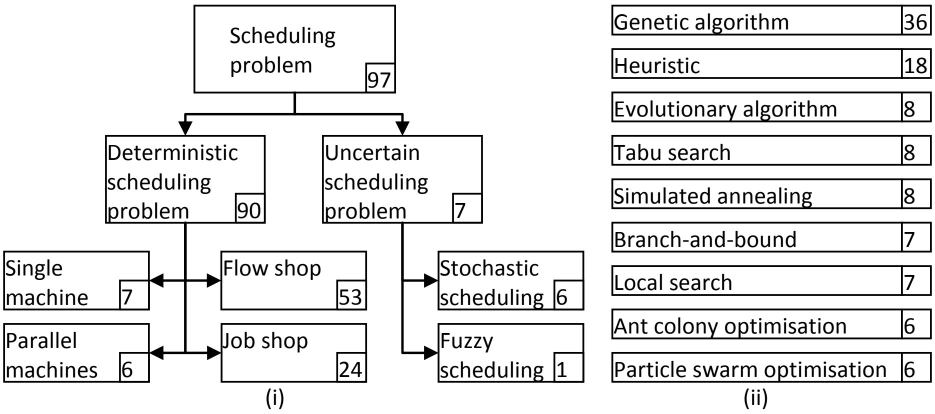


Figure 2.2: A classification of (i) scheduling problems with the number of reviewed papers and (ii) algorithms used for production scheduling with the number of reviewed papers except the algorithms cited less than three papers, based on [16].

[17] and Dutta & Fourer [18], are described in more detail as these papers provide a framework for reviewing other papers in this area.

Tang et al. [17] reviewed the tools and methods of production planning and scheduling for integrated steel production. They mentioned four approaches for production planning, namely: operation research based methods, artificial intelligence (expert system, intelligent search, constraint satisfaction), asynchronous team methods (whereby a problem is re-solved by many methods) and human-machine coordination techniques. Most of the papers on these methods are case- and/or process specific.

Another review of methods is provided by Dutta and Fourer [18]. In contrast to Tang et. al., these authors provided classification of planning and scheduling problems solved by mathematic programming applications. They identified six types of planning problems in integrated steel plants: 1) national steel planning; 2) product-mix optimisation; 3) blending in blast furnaces, coke ovens, or steel foundries; 4) scheduling, inventory, and distribution; 5) set covering; and 6) cutting stock optimisation.

2.2.3 Optimisation techniques

Roy, Hinduja and Teti [47] wrote a comprehensive literature review on engineering design optimisation, where they classified optimisation techniques by the five major groups

Reference	Problem	Approach
As'ad & Demirly [19]	Steel rolling mill	Built-in branch and cut algorithm
Tang, Guan, & Hu [20]	Steel alloy converter & transportation to refining furnaces	Tabu search
Xue, Zheng, & Yang [21]	Steel casting	Particle swarm optimisation, travelling salesman problem
Tang & Wang [22]	Hot rolling of heavy plates	A two stage: scatter search, and decision tree based heuristics
Tang & Wang [23, 24]	Colour-coating	Tabu search
Atighehchian, Bijari, & Tarkesh [25]	Steel-making continuous casting scheduling	A combination of ant colony optimisation and non-linear optimisation algorithm
Pan & Yang [26]	Large scale rolling batch scheduling problem	A variant of column generation
Vanhoucke & Debels [27]	Integrated steel company	A two stage: local search machine assignment, and optimal knapsack solver
Missbauer, Hauber, & Stadler [28]	Steel-making continuous casting	Heuristics
Wang & Tang [29]	Hot rolling	Tabu search, manual scheduling, Serial scheduling
Tang & Wang [30]	Colour-coating	Reactive scheduling
Mathirajan, Chandru & Sivakumar [31]	Heat-treatment furnaces	Heuristics
Huegler & Vasko [32]	Meltshop	A combination of heuristics with either generation evolutionary programming, steady state evolutionary programming, or simulated annealing
Tang & Huang [31]	Tube rolling	Branch and bound, neighbourhood search
Tanizaki, Tamura, Sakai, Takahashi, & Imai [33]	Multi-stage job-shop process with crane handling	Heuristics
Li, Li, Tang & Wu [34]	Tube hot rolling	Heuristics
Chen [35]	Hot charged rolling	Lagrangean decomposition
Kumar, Kumar, Tiwari, Chan [36]	A process including blast furnace, transporter, meltshop, continuous caster, and coil hot strip mill	Heuristcs
Appelqvist & Lehtonen [37]	Integrated steel company	Branch-and-bound
Singh, Srinivas & Tiwari [38]	Steel rolling	Parallel genetic algorithm
Roy, Adesola, Thornton [39]	A generic steel-making process	Heuristics
Ouelhadj, Petrovic, Cowling, Meisels [40]	Continuous caster and hot strip mill	Inter-agent cooperation, and tabu search
Neureuther, Polak, Sanders [41]	A steel fabrication plant	Hierarchical production planning
Cowling, Ouelhadj & Petrovic [42]	Steel casting and milling	Multi-agents with contract net protocol as an inter-agent cooperation
Tang Liu, Rong & Yang [43]	Slab stack shifting	Genetic algorithms
Park, Hong & Chang [44]	Hot coil making in a mini steel mill	Heuristics
Tang, Luh, Liu & Fang [45]	Steel-making, refining and continuous casting	A combination of Lagrangian relaxation, dynamic programming and heuristics
Van Voorhis, Peters, Johnson [46]	Steel casting with an impact to downstream processes	Heuristics

Table 2.1: Production planning and scheduling in steel manufacturing.

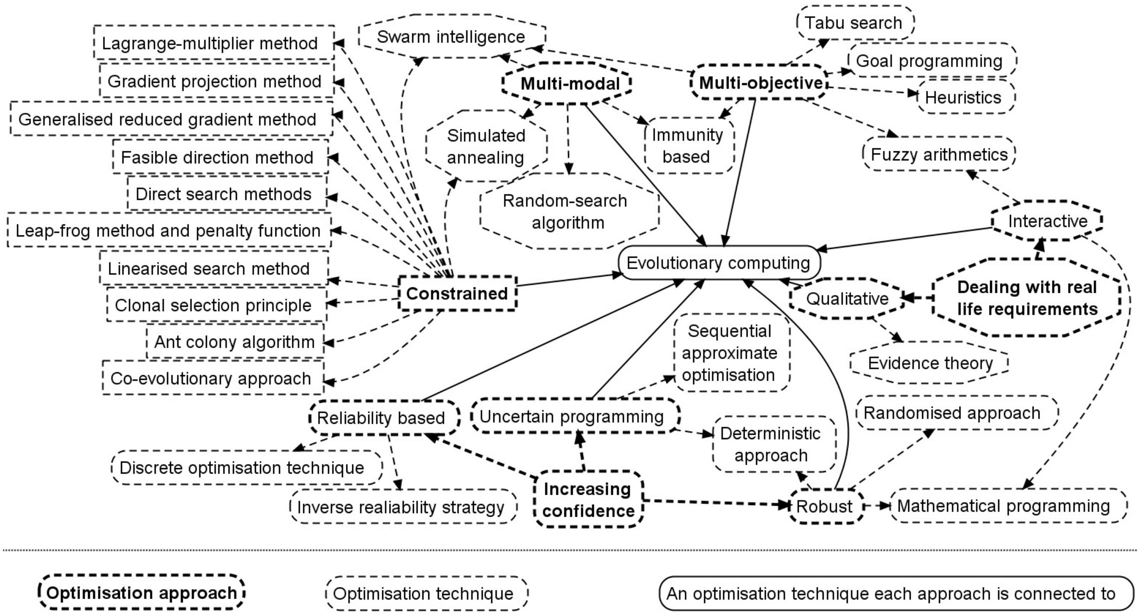


Figure 2.3: Problem-based classification of optimisation techniques, re-drawn from [48].

of optimisation problems. Problems can be 1) constrained (limitations on input parameters), 2) multi-modal (more than one optimal solution), 3) multi-objective (more than one criterion), 4) real life requirements (industrial case) and 5) increasing confidence (no explicit knowledge). Each problem is usually related to a group of optimisation techniques; however, some of the techniques are related to more than one type of problem. This classification is shown in Figure 2.3.

Roy et al. [48] provide a classification of techniques for engineering design optimisation. Production planning problems also are constrained, multi-modal, etc., which means that this classification may also be applied to the production planning domain. Figure 2.3 shows that evolutionary computing is the only technique used for solving all types of problems. Genetic algorithms are the most commonly used optimisation technique among evolutionary algorithms and optimisation approaches. Stockton et al. [49, 50] reviewed the use of genetic algorithms in operation management, which included planning optimisation. For these reasons, GA was selected as an optimisation technique for this research.

Content	Area		
	Manufacturing	Maintenance	Supply
Time-sequenced of products	[52, 53, 54, 55, 56, 12, 57]	[58]	
Dispatching rules	[59, 60, 61, 62, 12]		
Production parameters	[63, 64, 65, 66, 67, 68, 51, 69]	[70, 71, 72, 73]	[74]
Production site's layout	[75, 76, 77, 78]		[79]
Composite	[12]		[80, 81, 82]

Table 2.2: Five ways may result performance improvements of production systems using DES & GA.

2.2.4 Genetic algorithms and discrete event simulation

A common approach to computer modelling of complex production systems having dynamic and stochastic behaviour is discrete event simulation [1]. Developed and validated DES models provide trustworthy results that may be used to compare alternative production plans and schedules.

Some algorithmic optimisation approaches are more compatible with DES modelling than others. Classical optimisation approaches have certain disadvantages, i.e. traditional optimisation methods are case-based, and, therefore, are not generic [51]. On the contrary, evolutionary algorithms are suitable for use with DES due to the following characteristics [1, 9, 10, 11]: DES models are as unique as the respective production processes, have complex behaviour and noisy output, often incorrect inverse problems and discontinuous parameter change, incompact search space and many-extremes performance measure.

DES & GA were previously used to improve the efficiency of production systems. Andersson et al. [12] have mentioned direct and indirect methods to optimisation of production schedules. This binary classification might be extended on the basis of the chromosome's content. A new five-category classification was developed; papers on each category are listed in Table 2.2.

1. Time-sequenced introduction of products. In addition to the products, resources also may be introduced into a system in a form of time-sequenced chromosome.

Year	Authors	Method	Objectives	Application
1998	Azzaro-Pantel, C. *et al.* [52]	GA	average residence time	wafer manufacturing
2001	Oldenburg, N. *et al.* [53]	GA	overall production time	a multi-product plant
2003	Tedford, J. & Lowe, C. [54]	FLGA, compared with SPT, SLACK, FIFO, EDD	total processing time, flow time, average lateness, percentage of late orders	flexible manufacturing system
2005	Liu, Q.-L. *et al.* [55]	GA	coil stack throughput	steel manufacturing
2006	Song, D.-P. [56]	evolution strategy	cost of holding stock & tardiness	a capital goods company manufacturing stream turbines
2008	Andersson, M. *et al.* [12]	GA, compared with SPT, LPT, EDD, LBT, SBQ, HP	throughput, shortage, target levels, stopped in advance, setup times	camshaft manufacturing line
2009	Alfieri, A. [57]	tabu search	due date, time spent	cardboard production

Table 2.3: Optimisation of production schedules using DES model as a fitness function of GA and time-sequenced information encoded in chromosomes.

2. Dispatching rules. Examples of dispatching rules are shortest processing time (SPT), first in first out (FIFO), earliest due date (EDD).

3. Production parameters. Machine or conveyor processing speed, buffer size may be named as examples.

4. Production site's layouts. A number of machines and their location on production site are encoded in a chromosome.

5. Composite. A chromosome consists of two or more of the previously mentioned chromosomes.

Some of these approaches are not suitable for the optimisation of production plans or schedules of a steel manufacturing company. Modifications of a production site's layout are generally an inappropriate method for steel manufacturing due to massive and expensive equipment. Application of the optimised production parameters and dispatching rules would require a significant change in manufacturing procedures and personal training to be a generic solution for a multi-factory company, yet useful for individual projects. On the other hand, time-sequenced introduction of products is a generic method, which requires minor changes in operation management, production planning and sales departments. Papers on this category are explicitly described in Table 2.3.

Many GAs have been developed since this concept was introduced to the research society. These GAs were compared with each other on a variety of theoretical and industrial problems. NSGA-II is one of the algorithms which provided 'good' results for a wide variety of problems, and is one of the de-facto algorithms to use or compare against. For this reason, NSGA-II was selected for this research.

2.3 Cost estimation techniques

Cost estimation [83] is the 'process of predicting or forecasting the cost of a work activity or work output, depending on inputs from the cost analysis activity, which is the process of studying and organising past costs and future estimates.' The cost estimation process includes building a model to estimate cost of cost objects *i.e.* products and components, processes and operations, contracts and orders. Cost estimation is used [84] for feasibility studies, selection of alternative designs or investment proposals, appropriation of funds, and preparations of bids and tenders.

A wide variety of cost estimation techniques and their classifications were developed during recent decades. While different techniques were developed to estimate cost in different environments, classifications were developed for several reasons. A classification could simplify one's understanding. Ostwald *et al.* [85], Niazi *et al.* [86] and Curran [87] developed classifications that provide some insights about this knowledge domain. Other researchers satisfy an active function with their classifications; for example, Rush and Roy [88] link cost estimation techniques with the stages of a *product's life cycle* (PLC), which simplify the selection of an appropriate cost estimation technique on the basis of the relevant stage of PLC.

2.3.1 Overview of classifications

Ostwald and McLaren [85] developed a classification of cost estimation techniques on the basis of cost objects. If a company has the product as a cost object, then techniques

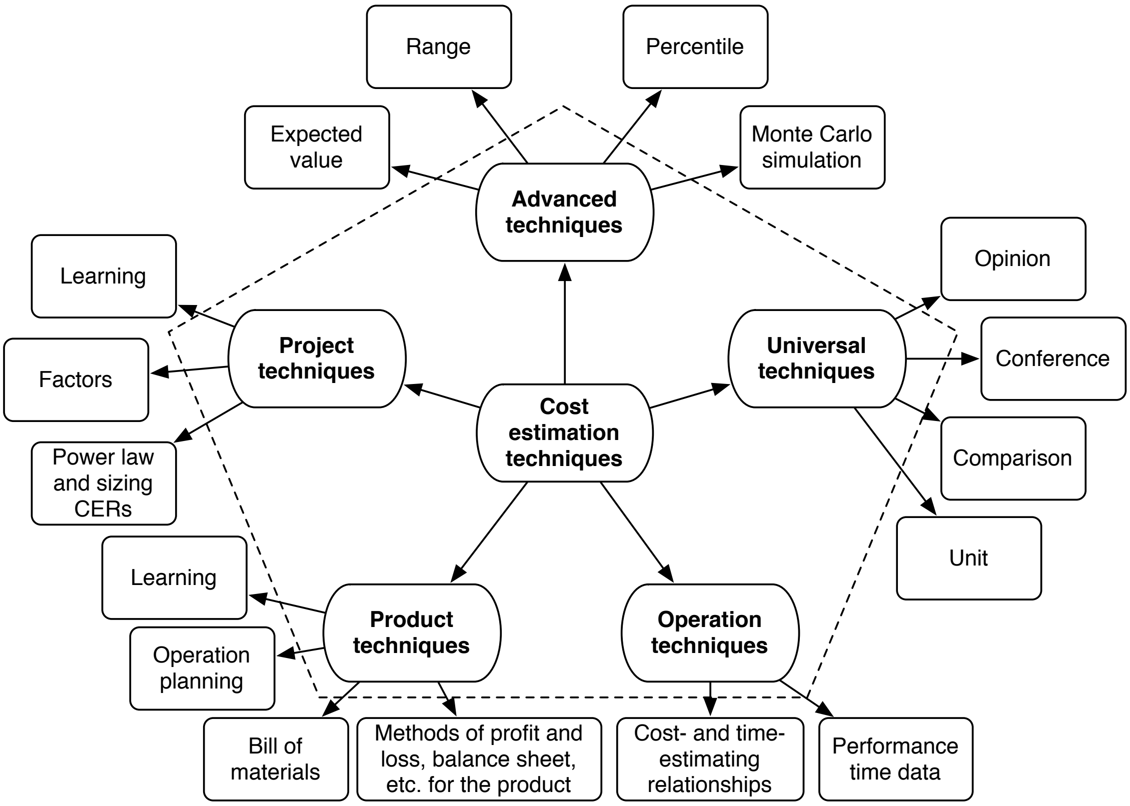


Figure 2.4: Classification of the product cost estimation techniques (is based on information from Ostwald and McLaren [85]).

such as *operation planning* or *bill of material* can be used for cost estimation, while the project as a cost object requires using techniques based on *learning*, *factors* or *cost estimation relationships*. This classification is shown in Figure 2.4.

PLC was the basis of the classification developed by Rush and Roy [88, 89]. If a company is innovating a product – a concept design phase of the product life cycle – then techniques such as *parametric estimation*, *case-based reasoning* or *feature-based costing* are the most appropriate for cost estimation. However, at the production stage this company would be recommended to shift to an *activity-based* or *detailed cost estimation*. This classification is presented in Table 2.4.

Niazi *et al.* [86] group product cost estimation techniques by their nature as being either qualitative or quantitative, and further subdivide them into smaller groups. For example, *activity-based costing* is a quantitative technique with an analytical nature. This classification narrows down Ostwald's classification [85] in the area of product

Stage of life cycle	PE	NN	CBR	FBC	ABC	DCE
Concept design phase (innovation)	+	−	+	+	−	−
Concept design (similar products)	+	+	+	+	−	−
Feasibility studies	+	+	+	+	−	−
Project definition	+	+	+	+	−	−
Full scale development	−	−	−	+	+	+
Production	−	−	−	+	+	+

Table 2.4: Cost estimation techniques and product life cycle (composed from Rush and Roy [88, 89]). *Parametric estimation* (PE), *neural-networks* (NN), *case-based reasoning* (CBR), *feature-based costing* (FBC), *activity-based costing* (ABC), *detailed cost estimation* (DCE); '+' indicates that the technique could be used within the stage, '−' means the opposite.

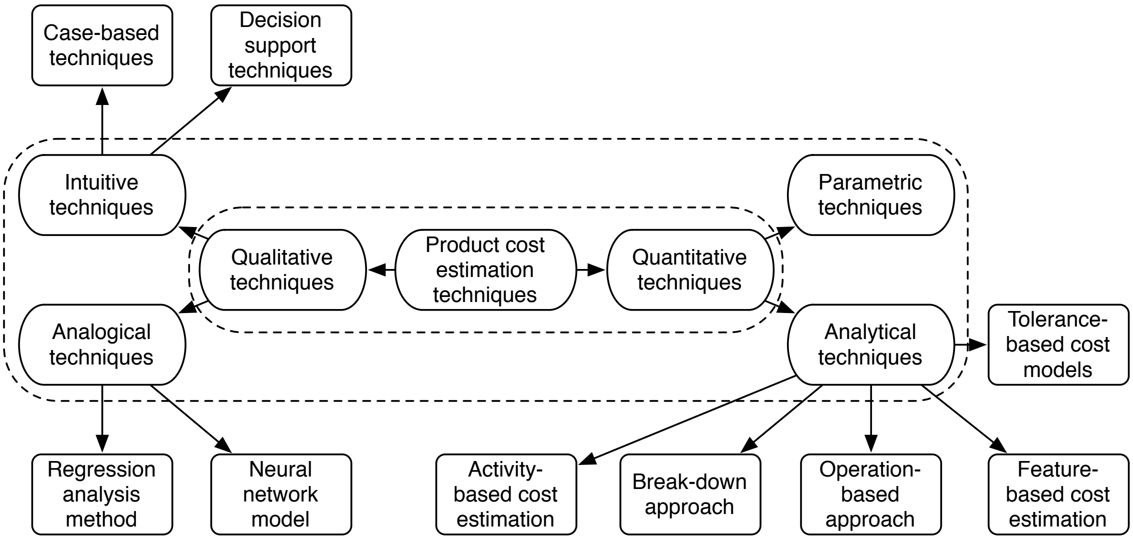


Figure 2.5: Classification of the product cost estimation techniques (re-drawn from Niazi *et al.* [86]).

cost estimation and provides some insights into the nature of these techniques. This classification is shown in Figure 2.5.

Curran *et al.* [87] observed cost estimation techniques in use by the aerospace industry and presented two classifications. The first is based on the state-of-the-art in aerospace cost estimation, and the second groups cost estimation techniques by the types of information processing. These classifications are combined together in Table 2.5.

Method	State-of-the-art		
	Classical	Advanced	Not mentioned
Aggregative	Bottom-up	Feature-based	LCC, Absorption, ABC
Relational	Parametric; Analogous	Neural networks, Fuzzy logic	Financial modelling, physical process modelling
Not mentioned		Uncertainty, Data mining	

Table 2.5: Classification of aerospace cost estimation techniques, Curran *et al.* [87].

2.3.2 Overview of cost estimation techniques

Activity-based cost estimation (*ABC*) was developed from an accounting approach called activity-based costing. This technique is used for the cost estimation of cost objects such as orders, batches, products, and services. The cost of an object is estimated by an accumulation of the activities' costs assigned to this object; all the costs come from the assigned resources. This technique utilises information elements [90, 91, 92] such as a resource cost, resource consumption per activity and activity time.

Feature-based cost estimation deals with the costs of the components' geometrical features. The geometrical information of a component is usually stored in a CAD/CAM model. The features can be related to specific manufacturing operations. By knowing the costs of operations, it is possible to calculate the cost of a product [86, 93, 94, 95].

Breakdown cost estimation is also known as detailed or traditional cost estimation. This technique estimates the cost of a product from the decomposition of a production process [86, 96, 97, 98] and requires detailed and systematic data about materials, labour, equipment, software, operational, support, *etc.* The cost of a product is aggregated from manufacturing, selling, and general and administrative expenses.

Operation-based cost estimation uses the cost of operations applied to a product. Usually, the cost of an operation is estimated by multiplication of an operation's cost rate by the processing time. The cost of a product is a summation of the operation's costs [86, 99, 100].

Parametric cost estimation uses the parameters of a product, such as weight, electricity consumption, and volume. An analytical function utilises these parameters for product cost estimation [86, 96, 101, 89]. *Tolerance-based cost estimation* is similar to *parametric technique* with manufacturing tolerance as the only parameter [86, 102, 103].

Case-based cost estimation uses similarities between products for cost estimation. An increased number of examples improves the accuracy and consistency of cost estimation. This technique is characterised by the use of expert opinions to select similar cases and parametric equations for cost estimation [86, 96, 104, 89].

Regression-based cost estimation processes a historical cost information and parameters of past products to estimate the cost of a new product. A variety of regression methods might be used for cost estimation [86].

Neural network model uses an artificial neural network for cost estimation. The neural network is trained on past cases. Parametric information of a product is used as the input to a neural network [86, 105, 106].

Decision support cost estimation techniques are used to help either a cost estimator to make decisions on the different stages of cost estimation or a designer in the design of a cost-effective product [86].

2.4 Discrete event simulation

2.4.1 Overview of simulation modelling techniques

'A simulation is the imitation of the operation of a real-world process or system over time' [1]. It starts with building a model on which to run simulation experiments. A model may have different natures. Fishman [107] suggests that a model is described with three binary classes, whereby a model is either natural or man-made, open or closed, and either adaptive or non-adaptive. A combination of these binary classifiers defines the class of a simulation model; for example, it can be man-made – closed – adaptive, or man-made – open – adaptive.

Banks *et al.* [108] provides another classification, saying that simulation models are either static or dynamic, deterministic or stochastic, and either discrete or continuous. Static simulation models represent a snapshot of a system, while dynamic models introduce continuous time changes. 'Deterministic' means that no random events occur in

Variable	Time	
	Continuous	Discrete
Continuous	Partial Differential Equations, Ordinary Differential Equations, Bond Graphs, Modelica, Electrical Circuit Diagrams	Difference Equations, Finite Element Method, Finite Differences, Numerical Methods
Discrete	DEVS Formalism, Timed Petri Nets, Timed Finite State, Event Graphs	Finite State Machines, Finite State Automata, Petri Nets, Boolean Logic, Markov Chains

Table 2.6: Classification of modelling techniques according to the representation of time bases/state variables, re-drawn from Wainer [110].

a system, and the opposite is true in stochastic simulation models. Dynamic simulation has either discrete or continuous changes in its state.

Mitranil [109] describes the differences between continuous, discrete-time and continuous time-discrete events models. Wainer [110] further developed this concept stating that both variables and time could be either continuous or discrete, making four types of simulation modelling techniques. In Table 2.6, Wainer also listed simulation modelling techniques fitting each profile.

2.4.2 Comparison of simulation modelling techniques

Due to the number of elements, dynamic processing and a large variety of random events, production systems of Tata Steel Europe may be described as complex. Dynamic & numeric & stochastic techniques are suitable for modelling such systems. However, agent-based, discrete event, and system dynamics modelling techniques are used in slightly different conditions. These conditions are described in Table 2.7 and Table 2.8. With the Tata Steel Europe's expertise in DES, this modelling technique is the most preferable choice for Tata Steel Europe. That confirms the decision to use DES for cost estimation and production planning.

2.4.3 Discrete event simulation modelling

According to Banks' classification [108], discrete event simulation is a dynamic, stochastic and discrete simulation modelling technique; a continuous time-discrete event ac-

DES	ABS
In the process-oriented (top-down modelling) approach; the focus is on modelling the system in detail, not the entities. Top-down modelling approach. One thread of control (centralised). 'Passive entities' means that something is done to the entities while they move through the system; intelligence (e.g. decision making) is modelled as part of the system. Queues are a key element. Flow of entities through a system; macro behaviour is modelled. Input distributions are often based on collect/measured (objective) data.	Individual based (bottom-up modelling approach); focus is on modelling the entities and interactions between them. Input distributions are often based on theories or subjective data. No concept of flows; macro behaviour is not modelled; it emerges from the micro decisions of the individual agents. No concept of queues. 'Active entities' means that the entities themselves can take on the initiative to do something; intelligence is represented within each individual entity. Each agent has its own thread of control (decentralised). Bottom-up modelling approach.

Table 2.7: Comparison of DES and agent based simulation (ABS) models [2].

DES	SD
Tactical/operational. Models open loop structures – less interested in feedback. Analytic view. Narrow focus with great complexity & detail. Quantitative based on concrete processes. Use of random variables (statistical distributions). Black-box approach. Provides statistically valid estimates of system performance.	Strategic. Models causal relationships and feedback effects. Holistic view. Wider focus, general & abstract systems. Quantitative & qualitative, use of anecdotal data. Stochastic features less often used (averages of variables). White-box approach. Provides a full picture (qualitative & quantitative) of system performance.

Table 2.8: Comparison of DES and system dynamics (SD) modelling [3].

cording to Mitranil [109]; and a continuous time – discrete variable by Wainer [110]. The following example describes discrete event simulation. A production system consists of three machines; the production time of each machine is 10 minutes per unit regardless of a product; no setup or maintenance is required. Three units of different products are processed within this example. However, production of product 1 requires all machines, product 2 requires machines 2 and 3, while product 3 requires machine 3 only. There are no limitations on resources, stores/buffers are assumed to be unlimited and transportation takes no time. This example is visualised in Figure 2.6.

Events in a discrete event simulation model are **discrete**; therefore, changes occur at particular **events**. The introduction of a product into a model or start/end of product processing by a particular machine are the examples of events. The nature of discrete event simulation modelling is shown below using best- and worst-case scenarios. Table 2.9 shows that a change of time (and sequence) parameter makes a big difference even in this very simple example.

Best-case scenario takes 30 minutes	Worst-case scenario takes 50 minutes
1. At time 0 Products 1, 2, and 3 are introduced into the model 2. At time 0 Product 1 enters the input buffer of Machine 1, Product 2 – Machine 2, Product 3 – Machine 3. 3. At time 0 Machine 1 starts processing of Product 1, Machine 2 – of Product 2, and Machine 3 – of Product 3. 4. At time 10 (minutes) Machine 1 finishes processing of Product 1, Machine 2 – of Product 2, and Machine 3 – of Product 3. 5. At time 10 Product 1 enters the output buffer of Machine 1, Product 2 – Machine 2, Product 3 – Machine 3. 6. At time 10 Product 1 enters the input buffer of Machine 2, Product 2 – Machine 3, and Product 3 leaves the model. 7. At time 10 Machine 2 starts processing of Product 1, Machine 3 – of Product 2. 8. At time 20 Machine 2 finishes processing of Product 1, Machine 3 – of Product 2. 9. At time 20 Product 1 enters the output buffer of Machine 2, Product 2 – Machine 3. 10. At time 20 Product 1 enters the input buffer of Machine 3, and Product 2 leaves the model. 11. At time 20 Machine 3 starts processing of Product 1. 12. At time 30 Machine 3 finishes processing of Product 1. 13. At time 30 Product 1 enters the output buffer of Machine 3. 14. At time 30 Product 1 leaves the model.	1. At time 0 Product 1 is introduced into the model. 2. At time 0 Product 1 enter the input buffer of Machine 1. 3. At time 0 Machine 1 starts processing of Product 1. 4. At time 10 Product 2 is introduced into the model, and Machine 1 finishes processing of Product 1. 5. At time 10 Product 2 enters the input buffer of Machine 2, and Product 1 enters the output buffer of Machine 1. 6. At time 10 Machine 2 starts processing of Product 2, while Product 1 waits in the input buffer of Machine 1. 7. At time 20 Product 3 is introduced into the model, Machine 20 finishes processing of Product 2, and Product 1 waits in the input buffer of Machine 1. 8. At time 20 Product 3 enters the input buffer of Machine 3, Product 2 enters the output buffer of Machine 2, and Machine 2 starts processing of Product 1. 9. At time 20 Machine 3 starts processing of Product 3, while Product 2 waits in the input buffer of Machine 3. 10. At time 30 Machine 3 finishes processing of Product 3, Machine 2 finishes processing of Product 1, while Product 2 waits in the input buffer of Machine 3. 11. At time 30 Product 3 enters the output buffer of Machine 3, Product 1 enters the output buffer of Machine 2, Machine 3 starts processing of Product 2,. 12. At time 30 Product 3 leaves the model, while Product 1 waits in the input buffer of Machine 3. 13. At time 40 Machine 3 finishes processing of Product 2, while Product 1 waits in the input buffer of Machine 3. 14. At time 40 Product 2 enters the output buffer of Machine 3, and Machine 3 starts processing of Product 1. 15. At time 40 Product 2 leaves the model. 16. At time 50 Machine 3 finishes processing of Product 1. 17. At time 50 Product 1 enters the output buffer of Machine 3. 18. At time 50 Product 1 leaves the model.

Table 2.9: Best- & worst-case scenarios.

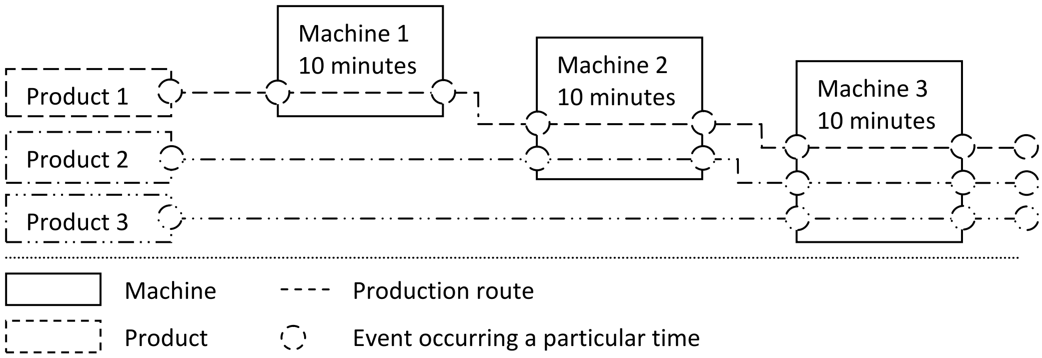


Figure 2.6: Simple production system.

This example shows the behaviour of a very simple model. Real production systems, even those having three machines, are much more complex for numerous reasons: products and resources might be delayed, buffers and resources are limited, machines require setup and maintenance, products might get damaged during the processing, workers take tea breaks from time to time, employees make mistakes, etc. These events affect the dynamics of a simulation model and have their own causes and effects; however, for the purpose of simplification, these events are treated as **stochastic**.

2.4.4 Life cycle of DES modelling projects

The life cycle model is 'a framework containing the processes, activities, and tasks involved in the development, operation, and maintenance of a software product, spanning the life of the system from the definition of its requirements to the termination of its use' [111]. This concept is widely used by many academics, presenting a minor variance in stages of the life cycle of a simulation modelling project. Different simulation life cycles are shown in Table 2.10; '+' symbol shows that an academic uses a stage and blank cell in the opposite case.

A graphical representation of Banks' life cycle [108] is shown in Figure 2.7. Each of these stages has their own function, which is clearly defined by its name. The literature was studied in order to identify current issues with DES modelling and expectations for DES in the future; these points are listed in Table 2.11 and Table 2.12.

Stages	References					
	[112]	[113]	[114]	[108]	[115]	[116]
Problem definition	+	+		+	+	+
Setting of objectives and overall project plan			+	+	+	+
Conceptual model design	+		+	+	+	+
Data collection				+	+	
Model building or translation		+	+	+	+	+
Model testing or verification and validation	+	+		+	+	+
Design of simulation experiments	+			+		
Model execution or experimentation	+	+	+	+	+	+
Output analysis	+	+	+	+		+
Model optimisation	+					
Model deployment or implementation	+	+		+		

Table 2.10: Life cycle of simulation modelling projects; '+' symbol shows that an academic uses a stage and blank cell in the opposite case.

Stage	Current issues
Problem formulation, setting objectives and overall production plan	Simulation as facilitation/problem structuring [117]. **Insuring that the problem statement is understood well enough** [118].
Model conceptualisation and data collection	**Better links with lean processes** [117]. **Conceptual modelling frameworks** [117, 6]. **Quick model development and easy to understand analysis** [117, 6]. Better support for data collection [117, 119].
Model translation, verification and validation	Integration of conceptual modelling and pre-modelling tools [117]. Scenario management [117]. Recommendations for a number of replications [117]. Guidance on scenario selection [117]. Design and analysis of experiments training for practitioners (not just another statistics course) [117]. Improved validation techniques [117, 6].
Planning, running and analysing experiments	Develop use of probabilistic sensitivity analysis [117]. Wider experimentation support [117, 6]. More options for exploring solution space [117]. Better visualization for experimentation [117]. Results management and analysis support [117].
Reporting results and taking actions	Sharing of simulation analysis via the Web [117]. Integration of simulation modelling methods into enterprise development methods [117]. Real-time experimentation to see the likely effect of making different decisions [117].

Table 2.11: Current issues and future expectations about DES grouped by stages of life cycle of DES modelling project. Bold font highlights partial coverage of a selected topic in this research.

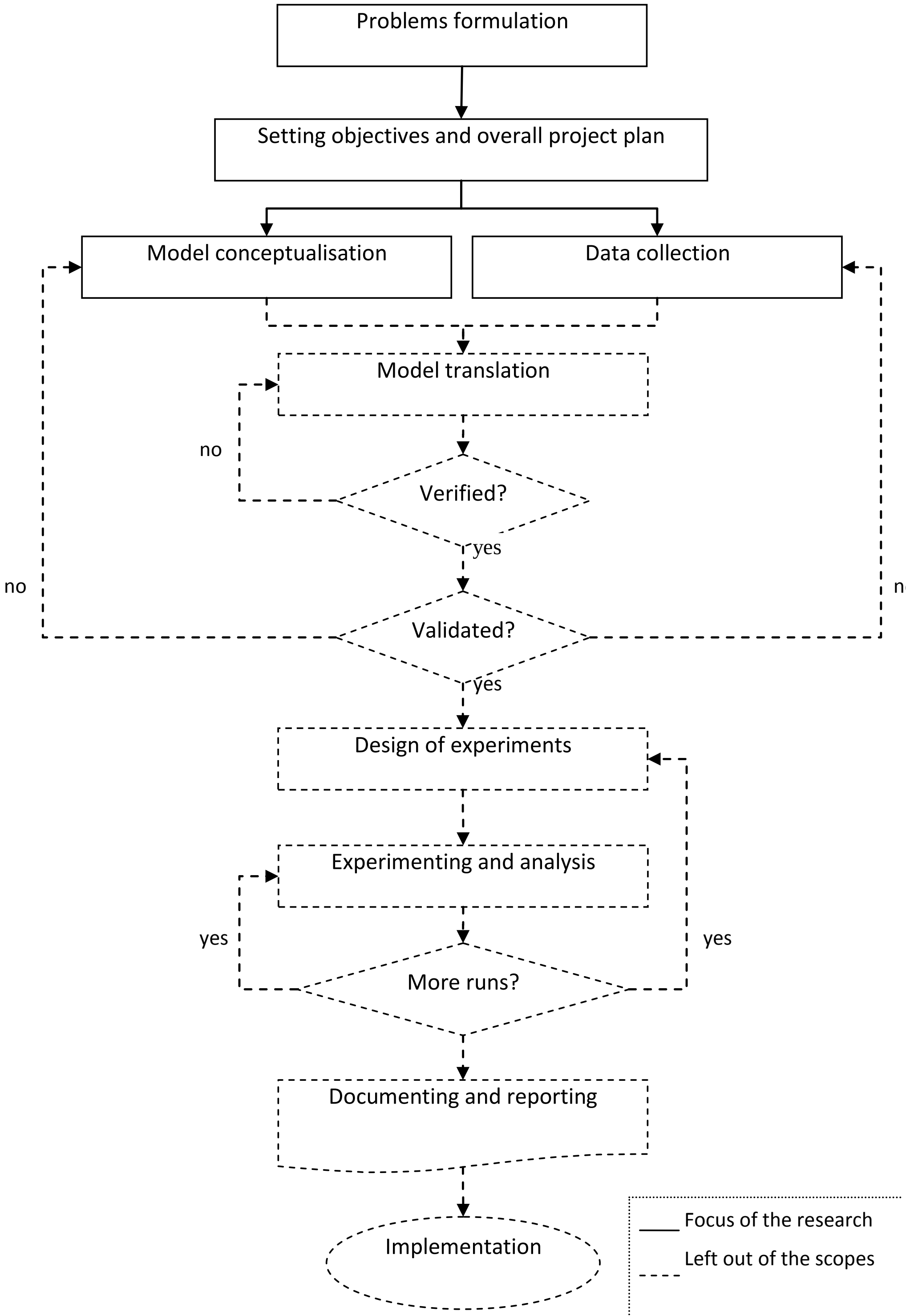


Figure 2.7: Methodology of DES modelling projects, re-drawn from [108].

Area	Current issues
Software	Better links between commercial off-the-shelf (COTS) simulation packages and physical simulators [117].
	Portability of models between COTS simulation packages [117].
	Discrete-event simulation and system dynamics conversion [117].
	Conversion between 'drag and drop' models and Java/C++ program code [117].
	Configuration of COTS tools [117].
	Open platform availability to run the widest platform [117].
	Distributed applications [117].
	Appropriate graphic libraries (cross package) [117].
	Amend CAD drawings and import into COTS simulation packages [117].
	Base simulation frameworks and libraries of tools [120].
	Customisation by derivation of specialised tools [120].
	Generic and specialised development environments [120].
	Easy expansion by derivation [120].
	Maintenance confined [120].
	Easy interoperability [117, 6].
Simulate	Embedded decision support algorithms (run dependent on decision points) [117].
	More niche modelling/embedded models [117].
	Support for domain templates [117, 6].
	Better links to process maps [117].
	Integrated lifecycle simulation [117].
	Different levels of usage [120].
	Balance the credibility of a model and its simplicity [118].
	'On-line' selection/implementation of variance reduction techniques for simulation optimisation [117].
	Better integration of optimisation with simulation tools [117, 6].
	Simulation for: **financial applications**, modelling human factors issue, emulation to aid the design of control systems, scheduling, predicting future performance (for example, the time to process an individual's insurance claim), real-time control, training [117, 6].
Manage	**Better facilitation of model/sub-model reuse** [117, 6].
	Books describing how COTS simulation packages can be used in different domains [117].
	Provision of run time and development licenses for COTS simulation packages [117].
	Standard for comparing simulation techniques [117].
	Standardized reuse of object-oriented simulations [117].
	Research into comparative cost of model development by COTS simulation package or by object-oriented programming [117].
	Availability [117].
	Manufacturing applications: material flow, constraint analysis [117].
	Applications to third world through non-government organizations and charities [117].
	Cheaper packages [117].
	Selection of the most appropriate tool for the job [118].
People	**Better support for group use of models** [117].
	Intuitive use [117].
	Better use of graphics and animated sequences [117].
	User-friendly interfaces [117].
	Deployment into user groups [117].
	User friendly patient flow simulations [117].
	Common terms and jargon [117].
	'Beginners' documentation [117].
	Easy web-based deployment for non-expert [117, 6].
	Easy to learn and easy to use [120, 6].

Table 2.12: Current issues and future expectations about DES grouped by generic concepts related to DES. Bold font highlights partial coverage of a selected topic in this research.

Costs	Elements			
	Entity	Process	Queue	Resource
Value added	+	+		
Non-value added	+			
Wait	+	+	+	
Other	+			
Total	+	+		+
Busy				+
Idle				+
Transportation	+			
Usage	+			+

Table 2.13: Arena cost model, '+' means that this type of cost is related to this element.

2.4.5 Cost estimation using discrete event simulation

As it stated in Section 6.2.1, a cost estimation technique is a combination of information processed by a method. DES is a method of information processing; therefore, it can be used for cost estimation. According to Sections 6.2.1 and Table 6.4, DES utilises a combination of process analytic with either product analytic or product parametric information. This way of estimating costs is based on the first architecture of cost estimation techniques and within this thesis is called a direct cost estimation. However, this research also describes a novel cost estimation technique and, as opposed to the direct cost estimation, this technique is called 'reversed' while also being called 'product family based' due to its basic characteristic.

The majority of DES modelling software packages have built-in functionality that supports cost estimation. The major DES modelling software of Tata Steel Europe is Rockwell Arena v11. A DES model is a combination of different elements; some of these elements – entity, process, queue and resource – are related to cost. A cost report may be automatically generated at the end of a simulation run; having different types of time, this report provides minimum, average and maximum costs for each element. Cost is calculated by the multiplication of time by the cost rate. In addition to this, a resource has both the cost of a single use, cost per idle time of use and cost per busy time of use, while an entity has initial and collected costs. Cost elements are listed in Table 2.13, while the algorithm of the cost estimation of Arena is described in Figure 2.8.

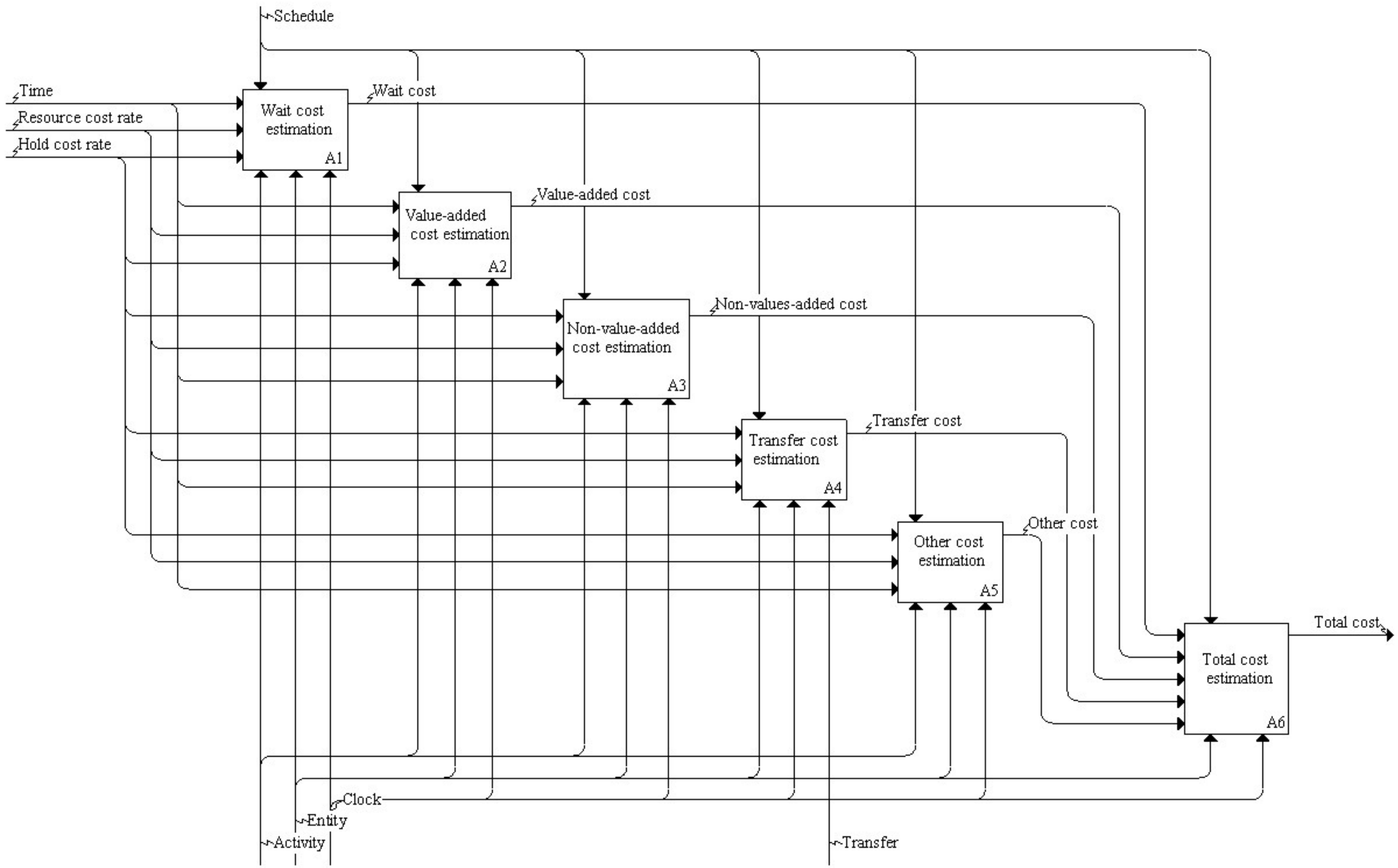


Figure 2.8: Cost estimation in Rockwell Arena v11

Direct cost estimation technique cannot work without a combination of process analytic with either product analytic or product parametric information. Because of this, a reversed cost estimation was developed; this technique is based on a number of ideas from existing cost estimation techniques.

The first idea came from activity-based costing [90]: a product's cost is based on the volumes of used resources multiplied by the cost of these resources. This concept can be transformed into: the cost of a product is proportional to the utilisation of the resources involved in the production of this product.

The second idea is described in the domain of computer simulation modelling, where a simulation model of a production process provides values of resource utilisation with the required level of accuracy. The combination of resource utilisation with the existing costs from standard costing system provides accurate relative costs of products.

'The rise of activity-based costing' began with a widely cited series of Cooper's papers having similar names; the first paper [121] was published in 1988. Another fundamental work on activity-based costing was published by Cooper and Slagmulder in 1999 [91, 92]. Many more articles on this topic have been published since then; some of these research topics were selected for presentation below to show the interests and findings of the research community.

Aderoba [122] developed a generalised cost-estimation model for job shops, while Ozbayrak *et al.* [123] used it for a comparison of push/pull advanced manufacturing systems. Ben-Arieh and Qian [124] covered the use of this technique in life cycle cost estimation for the design and development stage. Park and Simpson [125] used activity-based costing to estimate the cost of design for product families. Kaplan and Anderson [126] declared that time-based activity-based cost estimation, a technique which uses no resources but time, provides surprisingly precise results.

None of the observed papers on activity-based costing, or in the previously observed literature of cost estimation techniques in the production domain, except work of Curran *et al.* [87], has referenced the concept of using resource utilisation for cost estimation. However, the concept from Curran's paper, known as absorption costing, is known to cost the accounting community as the concept has different meaning to the idea of this research. Books on cost accounting provide the following definitions: 'Absorption costing is a method of stock costing in which all variable manufacturing costs and all fixed manufacturing costs are included as inventoriable costs' [127], another source provides a similar definition [128]. Absorption costing opposes variable costing, which is 'a method of stock costing in which all variable manufacturing costs are included as inventoriable costs. All fixed manufacturing costs are excluded from inventoriable costs; they are costs of the period in which they are incurred' [127].

Some of the research topics on absorption costing were selected for presentation. Absorption costing was compared with direct costing based on the criterion of the relevance of opportunity costs [129]. The effects of just-in-time systems on financial accounting metrics were checked [130]. A comparison of accounting methods including absorption costing, was performed based on the impact that inventory reduction affected the reported profit in a lean manufacturing system [131]. The analysis of the use of transfer pricing as a strategic device in divisionalised firms facing duopolistic price competition was performed [132]. The survey of factors influencing the choice of product costing systems in UK organisations was made [133].

The concept of product families was taken from books on lean manufacturing [134, 135]. Products are grouped into families on the basis of the unique combination of machines these products are going through. Each machine utilises a different combination of resources, which makes it possible to assign a consumption of resources to each product family. Having a discrete event simulation model for modelling a manufacturing system allows us to have precise values of the key performance indicator, including utilisation of machines. Discrete event simulation has a long history of modelling manufacturing systems; recently, DES started to apply it with the concepts of lean manufacturing. Within the examples of such papers worth mentioning are the study on benefits of using discrete event simulation together with lean manufacturing [136], and the use of simulation modelling as a tool to understand the concepts of lean manufacturing [137]. This combination was also tested on a number of case studies such as that involving engine test operations [138], sample management [139], and time variability analysis for factory automation [140].

There are not many papers covering cost estimation and resource utilisation, especially in the production domain; all meaningful alternatives in terminology and spelling were applied. None of these papers presents the concept of using resource utilisation for cost estimation in the way described in this section. Some of these papers were selected for presentation: parametric and neural cost estimation methods were compared; the quality of cost estimation would affect the utilisation of resources in further production [141]; with improvement of resource utilisation increasing the efficiency of factory operations [142].

2.5 Early stages of discrete event simulation

Robinson [6] commented that conceptual modelling (also called information modelling) lacks research [7, 8]. Similar concerns were raised by Skoogh & Björn [143], Hill & Onggo [144]. Perera & Liyanage [145] listed a number of factors that affect the development of conceptual models, starting with poor data availability, high-level model details, difficulty in identifying available data sources, the complexity of the system under investigation, lack of clear objectives, limited facilities in simulation software or packages to organise and manipulate input data and wrong problem definitions.

The major requirements for a solution are as follows: novice simulation engineers should be able to develop qualitative conceptual models of production systems, the developed conceptual models should support further cost estimation, the time of conceptual models' development should be reduced. For a potential re-use, these conceptual models should be stored in a knowledge base. Conceptual modelling shall be natural for production engineers who are inexperienced in simulation modelling. This is not the only solution, for example, Rampersad and Tjahjono [146, 147] propose use of DES modelling templates of manufacturing systems.

This research provides a solution for conceptual modelling, which, as described in Figure 3.8, is based on well-established methods from related knowledge areas. The areas are 1) cost estimation as the result of DES modelling is costs of products, and 2) manufacturing management as steel manufacturing is the background of this research.

Name of the technique	Arithmetic	Information	Used with DES
Activity-based costing	Yes	Yes	Yes
Feature-based costing	Yes	Yes	No
Breakdown cost estimation	Yes	Yes	No
Operation-based cost estimation	Yes	Yes	Yes
Parametric cost estimation	Yes	No	No
Tolerance-based cost estimation	Yes	No	No
Case-based cost estimation	No	No	No
Regression-based cost estimation	Yes	No	No
Neural network cost estimation	No	No	No
Decision support cost estimation techniques	No	No	No

Table 2.14: Cost estimation techniques for DES.

Adapting well-established methods for conceptual modelling could provide a complete and intuitive approach to information collection to be used in modelling.

The literature review showed that simulation modelling can be, and is, used for cost estimation. As stated in Section 6.2.1, a cost estimation technique is information processed with a special method. Having simulation modelling as a method of cost estimation and according to Table 6.4, simulation models usually utilise a combination of process analytic with either product analytic or product parametric information for cost estimation.

The initial selection of cost estimation techniques is based on three criteria similar to the requirements. 1) A well established technique means the technique is widely used by industry and is appreciated by academia; industrial cost estimation is mostly done by arithmetic cost estimation techniques [148]. 2) The second criterion is based on information cost estimation techniques are using; according to Table 6.4, simulation modelling techniques are using a combination of process analytic with either product analytic or product parametric information. 3) The third criterion is an actual practice of using a particular cost estimation technique with DES. The list of techniques with their descriptions is given in Table 2.14.

Activity-based and operation-based cost estimation techniques satisfy these criteria. These techniques are quite similar; however, activity-based costing is examined more thoroughly by academia (according to the number of related books) than operation-based costing. Activity-based costing was a matter of special attention of researchers

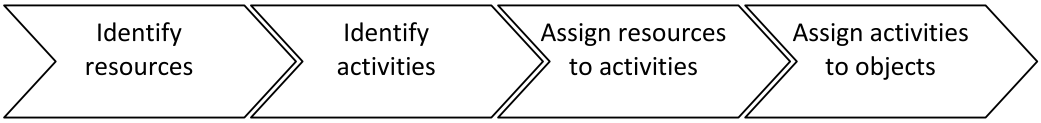


Figure 2.9: Simplified version of information collection in activity-based costing, based on [149].

Product family analysis	a) is breaking down the full product range into groups that can be managed together, or which share a significant part of value stream, b) the first step of value stream mapping [135]
Value stream mapping	is all the actions (both value added and non-value added) currently required to bring a product through the main flows essential to every product: (1) the production flow from raw material into the arms of the customer, and (2) the design flow from concept to launch [135]

Table 2.15: Selected lean tools.

in DES; therefore, activity-based costing was selected for adaptation. The author [149] developed a generic process of activity-based costing prior to this PhD project; this process is mostly based on research undertaken on a number of books and papers [150, 151, 123, 124]. A simplified version of this process is shown in Figure 2.9.

Manufacturing management requires development of information models of production systems. The 'code of practice' of advanced manufacturing management, lean manufacturing, is widely recognised as being an effective principle and tool for manufacturing management. According to Bicheno [135], lean manufacturing utilises a variety of tools. Two of them, i) product family analysis using product – process matrix and ii) value stream mapping were selected for adaptation for the information collection processes. A short description of these tools is provided in Table 2.15, while a generic process of information collection of value stream mapping is visualised in Figure 2.10.

2.6 Research gaps

The literature review was performed in order to clarify the systems of concepts related to the research objectives, identify current practices and solutions, as well as opportunities for future research. Obviously, these topics are too specific and are named considering

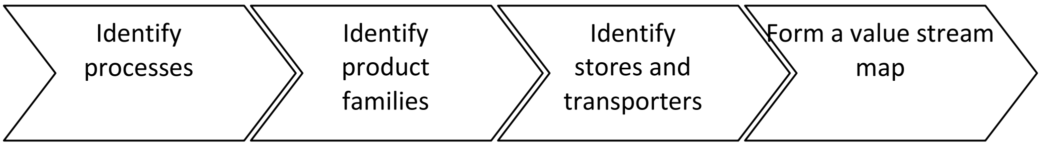


Figure 2.10: Information collection in lean manufacturing, from [134].

this literature review, the study of the company and hypotheses of the author. Three research gaps were identified during the literature review.

1. No research has been found on the optimisation of production plans using time-sequenced introduction of products into DES models used as fitness functions of the genetic algorithm.

2. No research showed the existence of simulation based cost estimation technique using information from a standard costing system.

3. No research was performed in structured information collection for further development of discrete event simulation models suitable for cost estimation.

Chapter 3

Research aim and methodology

3.1 Introduction

Research methodology is an important aspect of research. It describes how research is done, the methods and sequence of their application. Then, validation of the research outcomes is important because the 'right' method delivers 'right' results.

This chapter covers three main topics. Firstly, the aim and objectives of this research. Secondly, the methods applied to achieve this aim including research strategy, actual methods with their selection and research process. Thirdly, meta-analysis of the sources of objectivity and subjectivity with further detailed review into the most important sources of subjectivity.

3.2 Research aim and objectives

This research aims to develop frameworks for steel manufacturing planning capability improvement using discrete event simulation. In order to achieve this aim, a number of objectives have to be met.

1. To investigate state of the art use of DES in steel manufacturing and how cost estimation is performed within the environment.

2. To identify the industrial practice and challenges in use of DES in steel manufacturing.

3. Develop a framework to use DES for planning and scheduling optimisation.

4. Develop an improved cost estimation framework for steel manufacturing using DES environment.

5. Develop a framework for information collection to support DES model development of production systems in steel manufacturing.

6. Perform a systematic validation of frameworks using real life case studies.

The company have problems with production cost estimation and production scheduling; application of discrete event simulation modelling to these areas would increase the diversity of DES modelling. A framework that supports the development of discrete event simulation modelling would benefit both a number of developed DES models and longer use of DES models. In addition to studying the company, literature was also studied prior to the formulation of the following research objectives.

3.3 Research strategy

Robson [152] distinguishes the difference between strategy and tactics of a research. While strategy 'refers to the general broad orientation taking in addressing research', tactics means 'the specific methods of investigation'. This thesis contains separate subsections for the strategy and tactics of this research.

Research strategy is a broad orientation; a style of a research. Some aspects have been covered in the section on the philosophic basis of the researcher, Section 3.4.2, while the other is the set of principles that were addressed in this research. Some of these principles repeat those from Section 3.4.2, this is not a bad thing due to its importance and lack of knowledge of the absolute theory of scientific research.

Initial agreements are a must. This project was defined and received the funding prior to the assignment of a researcher. The researcher is merely a vehicle, an essential one, but still a vehicle that rides the roads of scientific discovery towards an aim. Certain academic and industrial questions, production planning, cost estimation, simulation model development, must be answered within this research. However, the specifics of the solution of those three things are up to science, the researcher and scope of this project.

The imperative of this research is related to three different knowledge areas consisting of production planning & scheduling, production cost estimation, and the development of simulation models of production systems. The relationships between them must be based not only on the functional level (capability improvement of production planning), but also on more the fundamental, methods-and-concepts level. This was achieved in two major ways, firstly with the functional outcome of one objective supporting another one (*i.e.* production cost is an important criterion in production planning) and secondly by using the same methods and concepts (*i.e.* product families are used in Chapters 5, 6, and 7).

Validity of the results. One of the principles of the science is validation. The Oxford dictionary provides the following definition of validity: 1) the state of being legally or officially acceptable, and 2) the state of being logical and true. Usually, a scientific research corresponds with both of these definitions. The former is rarely out of the scope; however, successful researchers remain in the records forever, or at least up to the unfortunate event of a global catastrophe, Nicolaus Copernicus, Charles Darwin or Albert Einstein are some of those, as they provided revolutionary and fundamental theories. This research remains in the field of normal science. (see Kuhn's work on scientific revolutions [153]).

A concept of 'black box' from theory of systems suggests three main components. An input, output and a hidden 'mechanism' of transforming input to output. A scientific research may also be represented with this concept. All of these three parts must be valid, including the initial agreement. Therefore, it must also be validated.

Describe the scope and its effect on the research. The scope does indeed affect a real world research. The impact comes from the knowledge areas involved (management is different to astrophysics), organisations involved (small design agencies are different to large production companies), the field of work involved (oil and gas is different to steelmaking), one large company from one part of the world is supposedly different from the same size business in another part of the world due to national differences and the specifics developed within old organisations, specific departments of one organisation involved (the cognition of a production manager [produce certain amounts of certain products within cost, quality, and time boundaries] differs to the cognition of a continuous improvement engineer [make production system more efficient by cost, quality or/and time criteria]).

The number of important elements or systems containing these elements is numerous. Each of them has minor or major impact to the inputs, 'black box', or outputs of the research. Also, a researcher will have different levels of impact to the elements of a researched system, while it is logical to take into account all important factors, it is sane to focus on the factors and elements that have the potential to have influence on a research, especially in the area of applied research.

3.4 Meta-analysis

Development of a real world model is the function of a scientific research. Such a model must be realistic and generic enough to be useful, must be complete and solid for the majority of researcher to agree on this model (it forms the current scientific paradigm in the case of normal science), must be verified and capable of passing tests of other researchers.

Scientific thinking is a method of developing such models. A researcher will know that a model, a simplified description of reality, is based on observations, assumptions and logical conclusions. A researcher shall know that his/er individuality affects the research. An 'ideal' researcher understands his/er subjectivity and decreases it with a number of methods which academia has developed over past centuries. Major methods used in this research are described in the following sections.

Meta-analysis of the research objects and methods clarify the major sources of subjectivity and objectivity. A concept-map is used for this. These elements are further categorised by two criteria: i) is this element a source of subjectivity or objectivity, and ii) is it a primary, secondary or tertiary by importance? Primary elements that introduce subjectivity to this research are explained, and this explanation is further used to define the research methodology.

3.4.1 Sources of subjectivity and objectivity

Scientific research provides the objective point of view of a research object. A research project contains a variety of elements that are the sources of subjectivity and objectivity. These elements, and the relationships between them, are listed in Figure 3.1. Each element performs its own function, for example, Tata Steel Europe funds the research that may be used to solve their problems, while it also provides information about the problems. Cranfield University provides research services to Tata Steel Europe and systematic research contributions to the society. In order to achieve that within this research, it utilised a structure of a PhD project with a proposal (to overview research aim, etc), a sequence of reviews (three, nine, twenty one and thirty month reviews) with reviewers and viva.

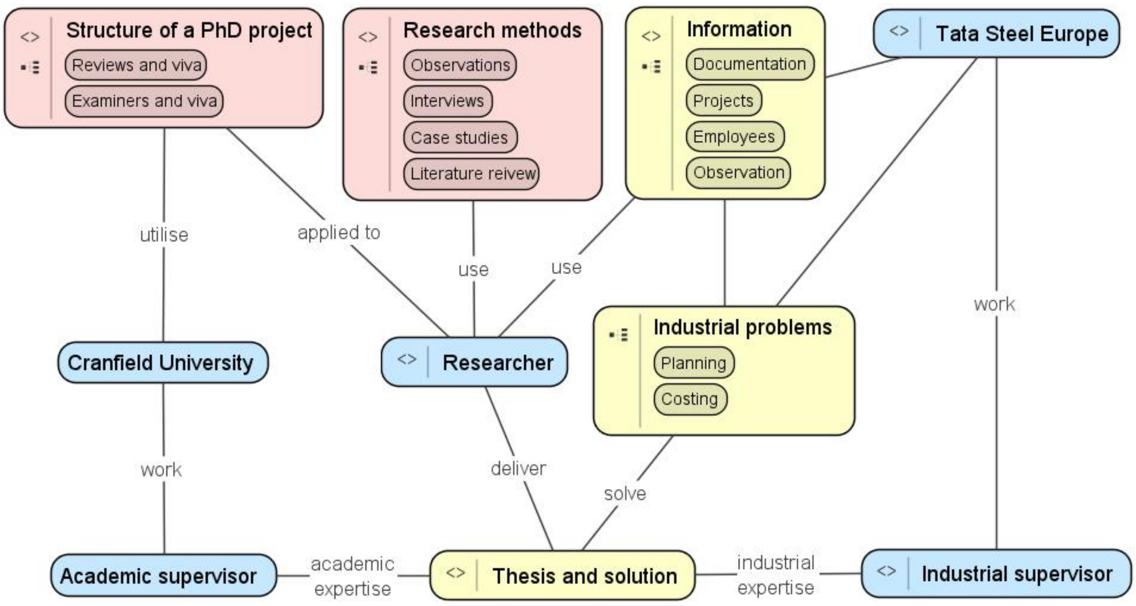


Figure 3.1: Main sources of subjectivity and objectivity of this research project.

Figure 3.1 contains a list of sources of objectivity and subjectivity of this research. Even though only the main sources are listed in this figure, some of them are primary,

Influence	Nature	
	Subjective	Objective
Primary	Researcher	Research methods
	Information	
Secondary	Industrial supervisor	Academic supervisors
	Academic supervisors	Structure of a PhD project
Tertiary	Tata Steel Europe	Cranfield University
	Cranfield University	

Table 3.1: Categorised sources of subjectivity and objectivity.

while others are secondary or ternary. These sources are categorised by the two dimensions. The first dimension defines either the subjective or objective nature of a source, while the second defines the influence to the project.

For example, a researcher is a primary source of subjectivity, as s/he is a person having his/er own understanding that makes a research, while an industrial supervisor is a secondary source of subjectivity as s/he affects the research through a researcher. An academic supervisor is a secondary source of both subjectivity and objectivity: having a proven record of objective research s/he understands the concept of scientific research; however, they are still human beings with a subjective understanding of the reality. These items are categorised in Table 3.1.

3.4.2 Philosophical basis of the researcher

Two books and one piece of research formed the author's point of view on science. Thomas Khun wrote the first book, *The structure of scientific revolutions*. This book provides a framework for concepts, which are related to science and scientific discovery. Eliyahu Goldratt wrote the second book, *The Goal: a process of ongoing improvement*; this book provides a 'scent' of science for industry. The third concept came from work of Bititci *et al.* [154, 155]; a generalised idea of this concepts may be formed as 'the function of a system that is equal to the purpose of this system'.

In the very first pages of his book, Goldratt [156] stated that 'Science is simply the method we use to try and postulate a minimum set of assumptions that can explain, through a straightforward logical derivation, the existence of many phenomena of nature.' And '... you basically have taken science from the ivory tower of academia and put it

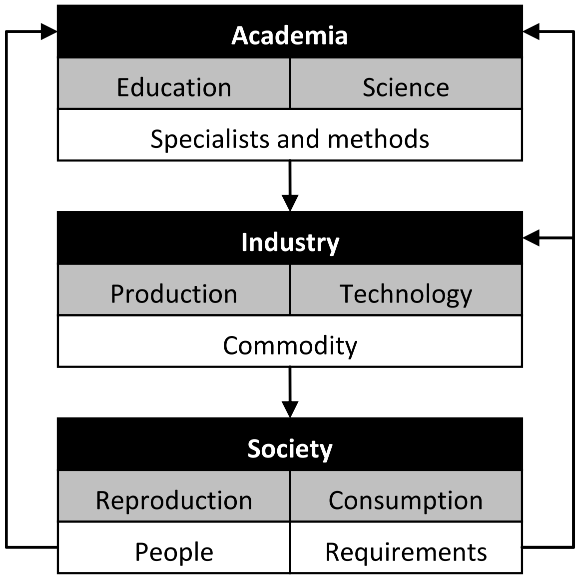


Figure 3.2: Simplified relationships between academia, industry, and society.

where it belongs, within the reach of every one of us and made it applicable to what we see around us.' In different words, science is a method for developing models of the world and developing approaches, methods and techniques that should be further used by industry to produce commodity for society; this point of view is visualised in Figure 3.2. Obviously, this is a simplified point of view on the relationships between academia, industry and society, because it is a projection, which is based on commodity production and circulation. However, as this research is focused on science for industry, these simplified relationships cannot harm this research.

Kuhn [153] formed a concept of scientific paradigm as 'Accepted examples of actual scientific practice – examples which include law, theory, application and instrumentation together, that provide models from which spring particular coherent traditions of scientific research.' Kuhn states the existence of two types of science, normal science explaining the world within the current paradigm, and revolutionary science, explaining the world with another paradigm, different to the current one. This research is based on normal science, the concepts used within this research are placed within the current scientific and research trends.

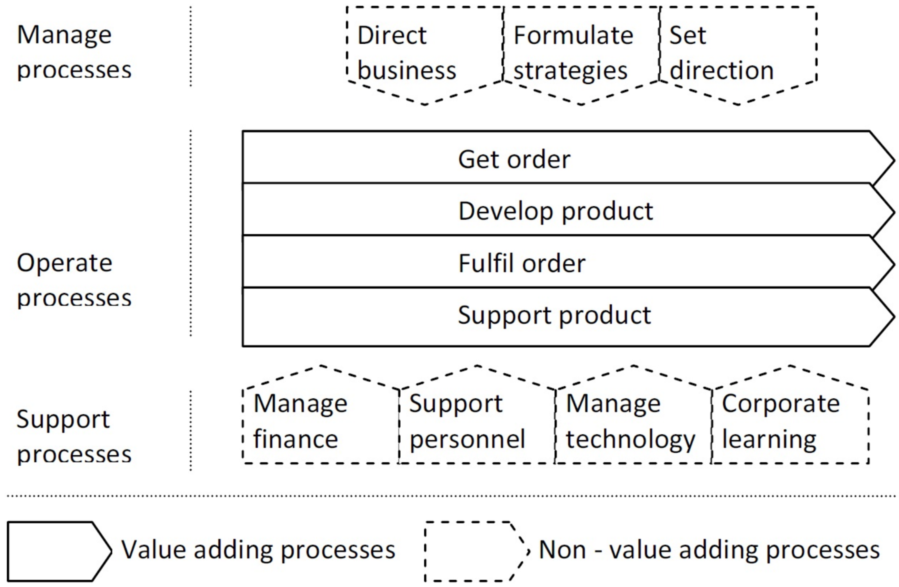


Figure 3.3: Business process architecture, re-drawn Bititci et al. [154, 155].

Bititci *et al.* [154, 155] describe an elegant architecture of business processes. On one side, processes can be either value adding or non value adding, while on the other side processes are either manage, operate or support processes as shown on Figure 3.3.

3.4.3 Flow of information

A certain amount of information is collected during this research project. Information is collected via document studies, interviews and observations. Information that is collected from a single source may be subjective, as it may not be complete or true. Some misrepresentations may be made during the information collection process due to a variety of reasons, for example, a source or the researcher may misinterpret facts, or information is intentionally modified by a source. An abstract process of information transfer is presented in Figure 3.4.

Objectivity comes from the information crosscheck of multiple sources, triangulation, logical reasoning, and academic knowledge. The results of research are further validated via the activities of the researcher, and the expertise of supervisors and examiners.

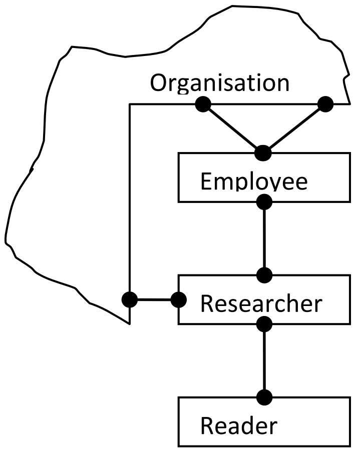


Figure 3.4: An abstract process of information transformation; despite the objects – organisation, researcher – the black dots represent areas of subjectivity.

3.4.4 Impact of discrete event simulation

Discrete event simulation and *genetic algorithms* are applied to *cost estimation* and *production planning & scheduling*. Each of these objects introduces some specifics to the research; however, in the author's opinion, discrete event simulation modelling has the most impact to the research methodology. An explanation of that is briefly provided in Figure 3.5; as the result, a single simulation modelling project may share some similarities with other projects, but will never share all of them. DES modelling projects are unique, and single organisations, even as big as Tata Steel Europe, can not provide enough to study them using structured approaches. Due to these reasons, for a researcher studying discrete event simulation modelling in a single organisation, unstructured interviews are more suitable than formal interviews, and participant observation is more suitable than structured observation.

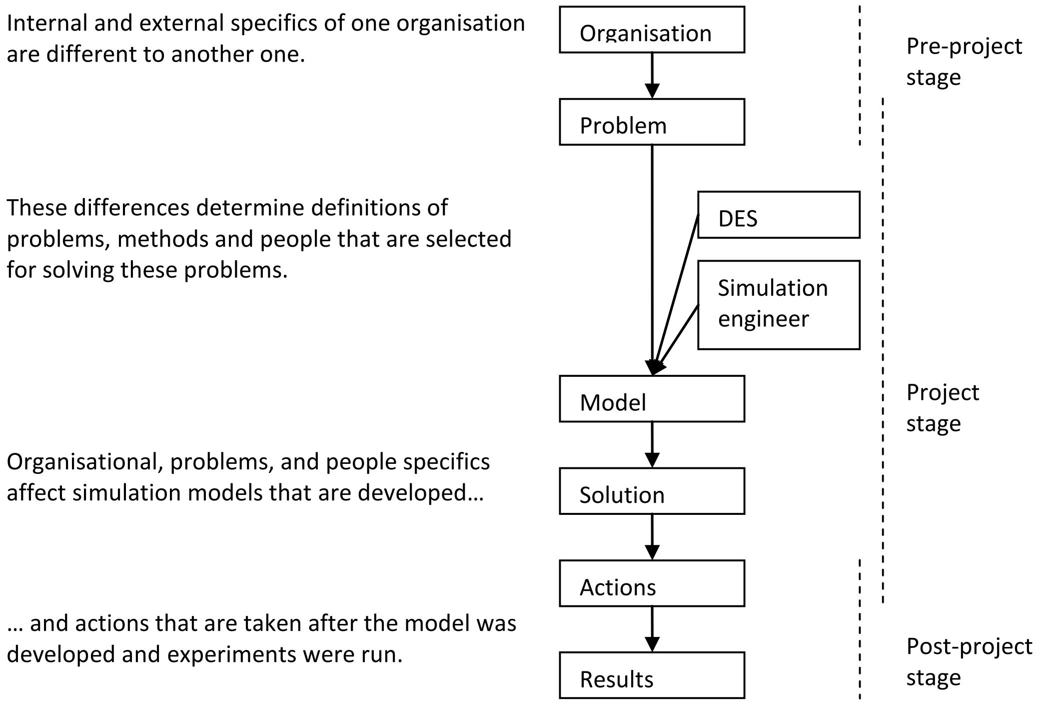


Figure 3.5: Uniqueness of simulation models.

3.5 Selecting research methods

3.5.1 Stages of a research project

A research project may be divided into a number of stages, such as proposal, overall study, specific research, validation of results and writing up. Even though these concepts may form a linear sequence, it is more likely that these stages must be formalised via fuzzy logic. However, a linear representation such as in Figure 3.6 is enough to highlight the major requirements for research methods.

3.5.2 Selection of the research methods

A variety of research methods were developed and used for research over the past few decades. Some of these research methods perform similar functions; however, in some situations, some methods are more preferable than others, for example, one chooses repetitive experiments to check a physical effect, and case studies if s/he works with

Name,	**functions & actions**, and	the **requirements** for research methods.
Proposal	Was done in the absent of the researcher.	No research is required except selecting the main statements and their validation during next stages.
Initial study	The researcher study the main concepts within the knowledge domains that are related to the research.	Reviewing literature for the main concepts, familiarisation with the research objects. These actions requires access to the major research databases.
Research	The researcher develops and checks a hypothesis, or perform a study of an research object.	Good hypotheses that are based on the current scientific paradigm, thorough study for the organisation, that requires considerable knowledge, intelligence, and access to the organisation.
Validation	The researcher validates the research findings.	Few real-life examples that can be used as case studies in order to validate the hypotheses. That requires the access to the organisation and hypotheses for test.
Thesis	The research is represented in a form of a well-balanced sequential story.	The writing of such a story requires considerable amount of knowledge and understanding of all aspects of the research and fine writing skills.

Figure 3.6: Stages of a PhD project.

a complex case that can not be repeated many times. Research methods are listed in Figure 3.7.

The same with this research, studying discrete event simulation modelling projects in a single organisation is not the case of experiments, structured interviews, etc. Otherwise, more informal methods, such as informal interviews and participant observation, are an appropriate choice to study DES modelling projects that are complex, diverse, and limited in numbers.

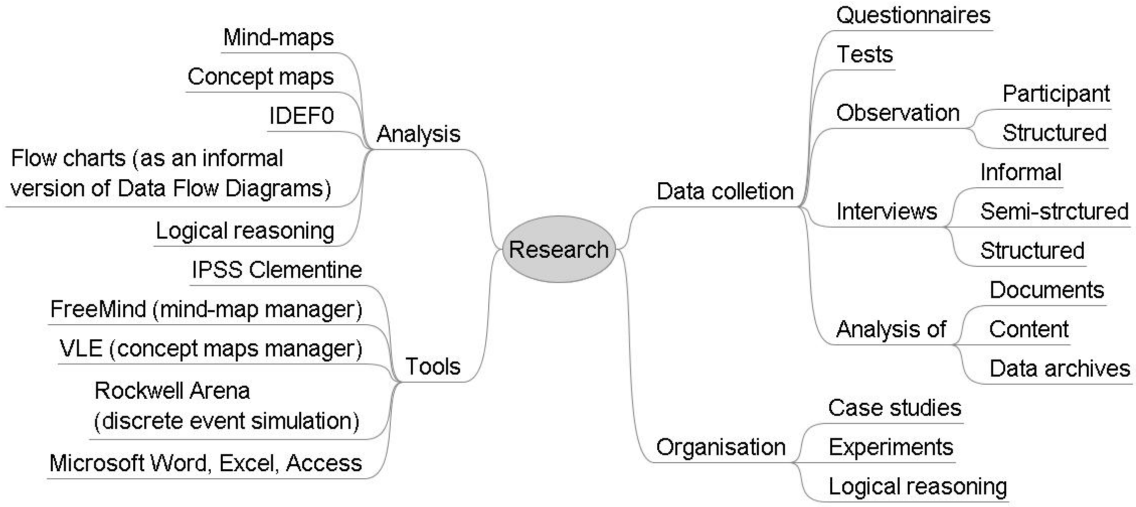


Figure 3.7: List of research methods, made from [152].

3.6 Research methods

3.6.1 Utilisation of the scientific paradigm

A research object is identified using the literature review and industrial request, and is described with concepts from the literature. It is assumed that different knowledge domains within one paradigm share some concepts and methods. It was also assumed that some knowledge domains contain concepts and methods, which does not exist in other domains within the paradigm. These 'unique' concepts and methods can be reused in other domains within one scientific paradigm. Because of these assumptions, the author followed a process of developing a solution for the problem.

This process starts with definition of problems and searches for this problem's solution within the knowledge domain. If no solutions are found, then related knowledge domains are reviewed for acceptable solutions. If there are any, one of them is adapted for the problems. If no solutions are found in the related domains, then a new solution has to be developed; this process is shown in Figure 3.8.

Tools of lean manufacturing were adapted for information collection for further development of discrete event simulation models of production systems (see Chapter 7); or the use of concepts from the theory of information, a technique is information with methods to process this information, to classify production cost estimation techniques

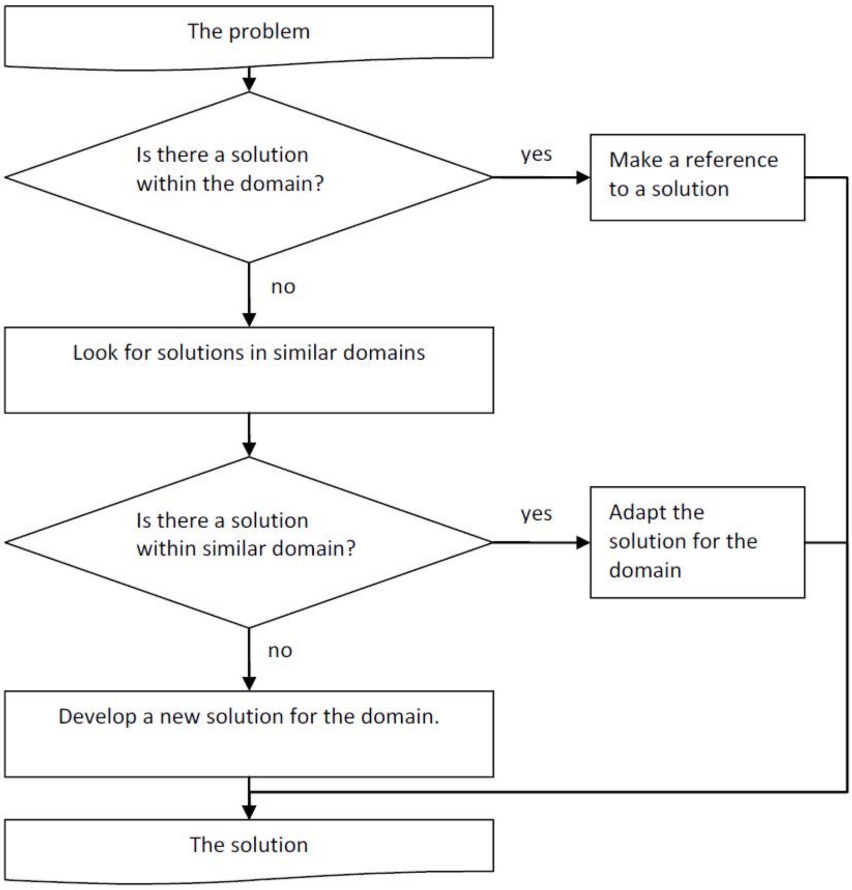


Figure 3.8: Developing a solution for a problem.

(see Section 2.3) are examples of the adaptation of methods from different knowledge domains. Reversed, product family based cost estimation technique (see Chapter 6) is a combination of knowledge reuse from different domains (a concept of product family from lean manufacturing) and an example of novel technique for production cost estimation.

3.6.2 Literature review

The literature review was used to familiarise the author with concepts related to the research objects, identification of research gaps, and research methods which might be used in this research. Few knowledge domains were reviewed during this research. There are different literature review approaches used by research society; however, they have the following main points, i.e. 1) a literature review has to be focused on a

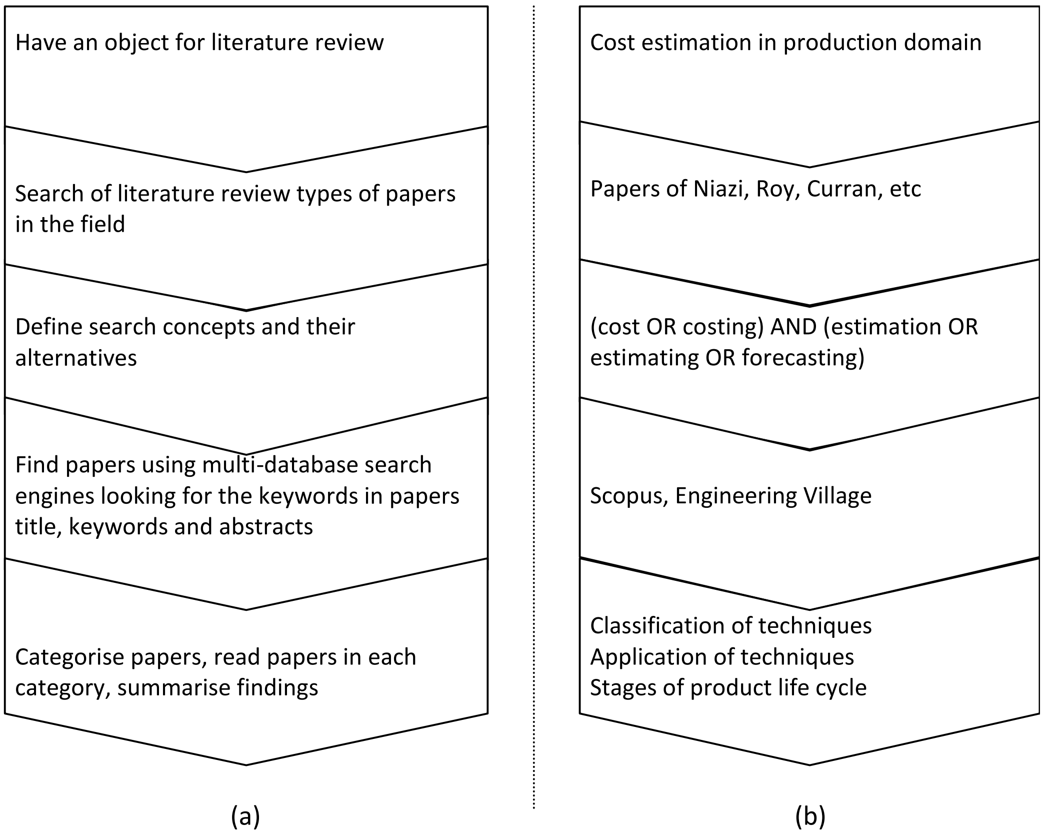


Figure 3.9: Process of literature review (a) stages of this process, and (b) example for each stage.

research problem, 2) a literature review has to be up to date, 3) a literature review has to be complete. These points are fulfilled by using a comprehensive set of keywords searching a few databases of scientific publications. The process of review is described in Figure 3.9.

3.6.3 Participant observations

Participant observations and unstructured interviews were used in this research. The rationale for selecting these techniques is based on the complex and fuzzy nature of the research objects; DES modelling projects of complex production systems with involvement of tacit knowledge that is collected from a limited number of employees playing different roles on different levels in one company.

Participant observation is a method of data, information, and knowledge collection by playing a functional role in a real-life situation or project. Directness, without the subject affecting the data, is a major advantage of this type of observation. Participant observation [152] is an appropriate technique to gain understanding on the complexity of the real world. The data collected by observation may add to the data collected by any other technique.

3.6.4 Unstructured interviews

Unstructured interview is another method of information collection. Prior to interviews, a researcher has a general interest on the research objects as well as the understanding of related system of concepts; however, an interview allows a natural flow of conversation with people related to his research object [152].

Unstructured interview is another method of information collection. Prior to interviews, a researcher has a general interest on the research objects as well as the understanding of related system of concepts; however, an interview allows a natural flow of conversation with people related to his research object.

3.6.5 Case studies

A case study [152] 'is a strategy for doing research which involves an empirical investigation of a particular contemporary phenomenon within its real life context using multiple sources of evidence.' Case studies were used for the validation of the developed process of information collection, cost estimation technique and comparison of new production planning & scheduling with 'standard' production scheduling.

As a single case study is a subjective piece of complex information, however, there are methods to counter its subjectivity and misinterpretation. Firstly, subjectivity of a case study may be countered by using a number of case studies. The common practice is three or more, and triangulation; analysis of a case study from different perspectives.

The second and third sources, the complexity of the case study, and obscure perception, are countered by using a well studied and solid paradigm of normal science.

3.6.6 Visual languages

A fundamental work of Miller [157] states that one can work with seven (+/- 2) concepts at a time. This limits the complexity of objects one can work with. Mankind developed many approaches to overcome this limitation. The most ancient and widely used is writing; however, visual languages have become a popular tool during the last decades.

This thesis contains more than fifty figures, most of them are used to describe certain semantics of one system of elements that are related to each other. These figures are drawn using different visual languages that might be roughly grouped into the overall semantics group and the specialised semantic group. The former is used for overall understanding, and languages such as mind-maps, concept-maps, and flow charts form this group. The latter is used for formal representation, and languages such as IDEF0 and entity-relational diagrams form this group. These visual languages are shown in Figure 3.10 .

Mind-maps are used to describe a single core concept. Concept-maps are used for interrelations of multiple concepts. Flow charts show the dynamics of a system and the decision making process. IDEF0 is used for a thorough representation of a process, while entity-relationship diagrams are used to design relational databases. The rest of the figures are either representative of some issues (such as Figure 4.24 that clarifies the specifics of cost estimation in Tata Steel Europe) or show the results of experiments on production planning (see Figures 5.12–5.15).

3.6.7 Codes, tables, and multi-criteria decision making

Visualisation is not the only approach that strengthens the analytical side of this research. Another is codification followed by the representation of codes in tables and further use of these tables and codes for analysis or synthesis. The process of multi-criteria decision-making is a formal use of codes and tables; this process is shown

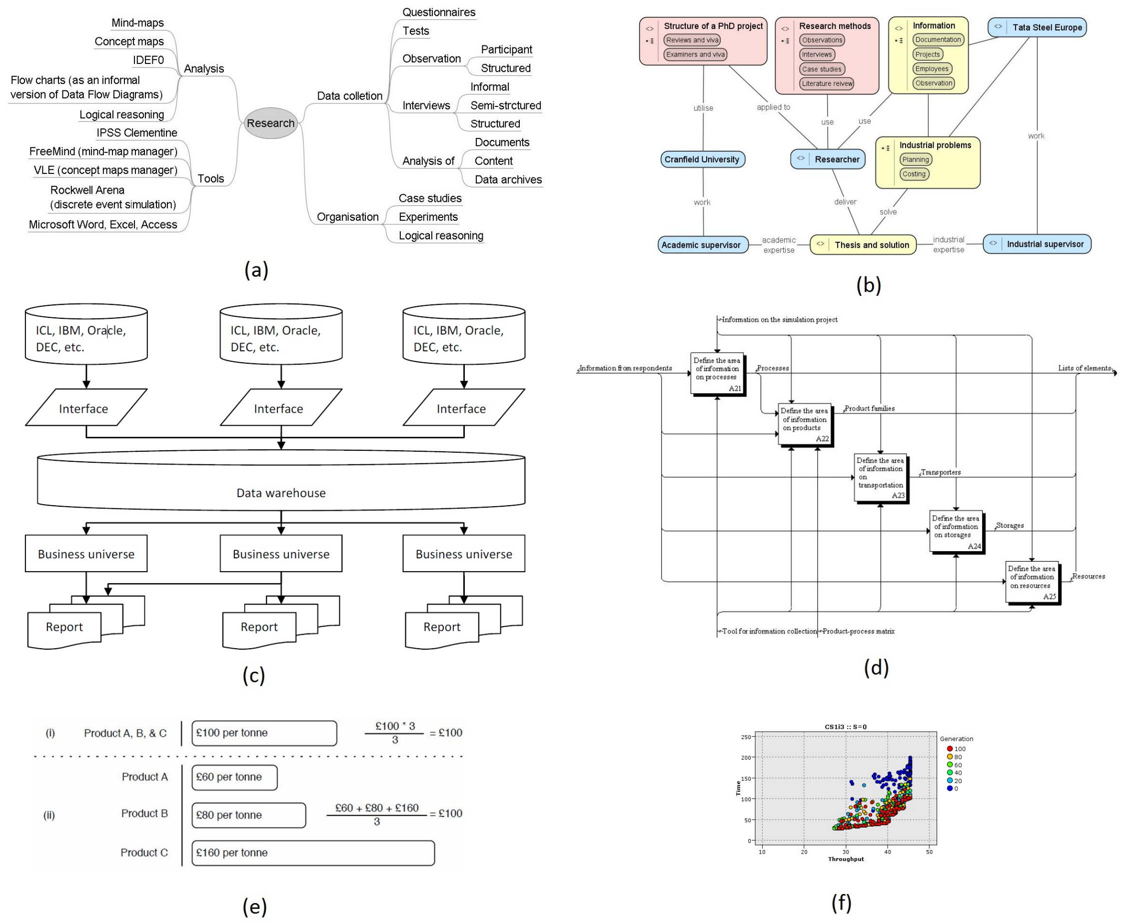


Figure 3.10: Visual languages that are used in this thesis, (a) mind-maps, (b) concept-maps, (c) flowcharts, (d) IDEF0, (e) a generic visualisation, (f) data representation from the planning experiments.

in Figure 3.11 This is a useful tool in the case of selecting one object within a few alternatives, applying both qualitative and quantitative criteria [158]. There are quite a few modifications of this technique, if the importance of criteria is the same, then Equation 3.1 is used.

$$R_j = \frac{\sum_{i=1}^{n} X_{j,i}}{n} \tag{3.1}$$

Where R is importance coefficient of an alternative, j - index of an alternative, X - value of a criterion; i - index of a criterion; n – number of criteria.

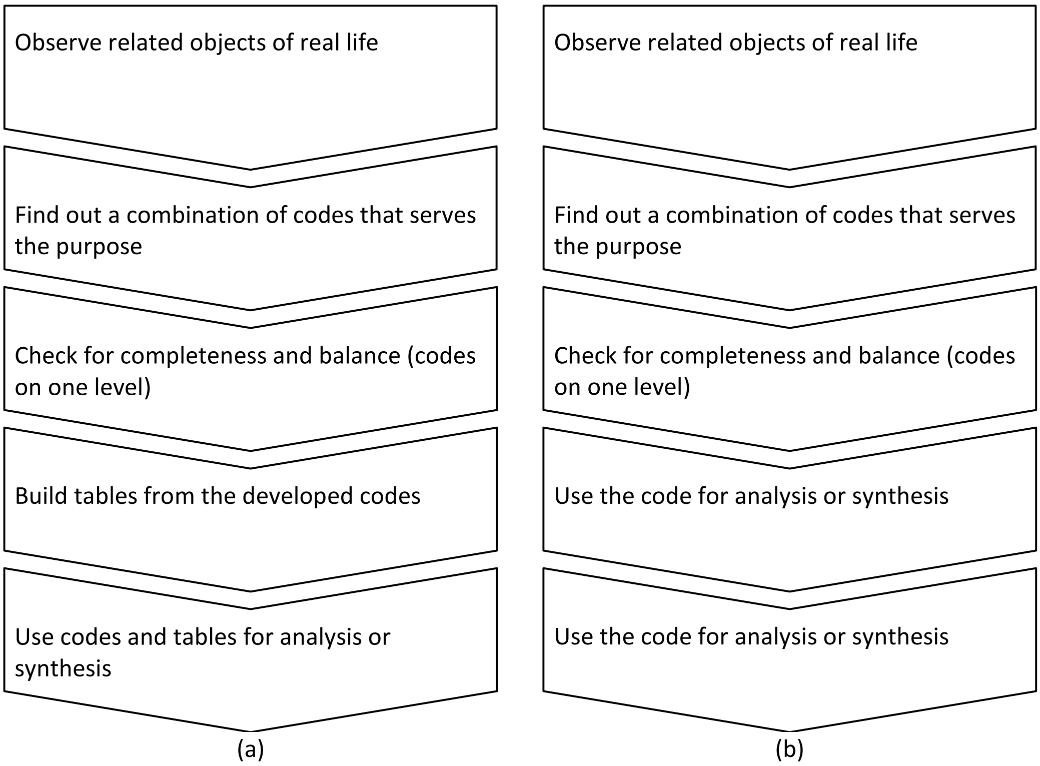


Figure 3.11: The process of using codes and tables for analysis and synthesis, (a) a process of few stages with examples of each stage on the part (b) of this figure.

3.7 Systematic validation

The author uses systematic validation of research concepts. Each concept is validated using a three by three matrix, or a bi-dimensional matrix with three levels on each dimension. The first dimension covers a system view to the concept, and it consists of super-system, system, and sub-system levels of a research concept. The second dimension covers the theoretical, realisation, and experimentation part of the research. The systematic view consists of nine elements, and if all of them are valid, then the researched is valid as well. Systematic validation of each research concept is described in detail in Sections 5.3, 6.6, and 7.3.

Each of the nine elements of the matrix is an important aspect of the research. Each element is described as follows: i) name of the object, ii) validation criteria, and iii) method of validation. These are described in Tables 5.1, 6.8, and 7.2. Each of the aspects is described in a separate section. Conclusions on the validity of the research are made at the end of each validation section.

3.8 Developing frameworks

The overall process of developing frameworks includes 1) selection of the research objects with rationale of this selection, 2) selection of research methods that correspond to research objects, 3) application of these methods and 4) discussion of these results followed by conclusions. Each stage should be capable of passing verification by experienced researchers in order to call this activity a scientific research.

Background information, requirements for industrial deliverables, problems and scope were given to the author at the beginning of the research project. Participant observations and unstructured interviews clarified and validated this information. The literature was reviewed for familiarisation with the concepts, listing the solutions for the problems and identification of research gaps. The majority of the solutions were developed by using well-established methods from other knowledge domains. These solutions were tested on a number of case studies. Interviews were performed with simulation engineers and other employees involved in DES modelling projects, namely, low- and medium-level manufacturing management, planning, sales and transportation. The author was also involved in a number of simulation modelling projects, playing roles from an analyst to a simulation engineer. The relationships between the major objects are shown in Figure 3.12.

Figure 3.12 shows the rationale for each objective. A solution to the next problem opens opportunities for future research. Thereby, after the optimisation part was finished, a project on the accurate cost estimation was initiated for two reasons, i) production cost is indeed a feasible optimisation objective and ii) it is a challenging area for Tata Steel Europe. Both optimisation and cost estimation systems require simulation models, therefore a tool that supports the simulation model development – an information collection process was developed.

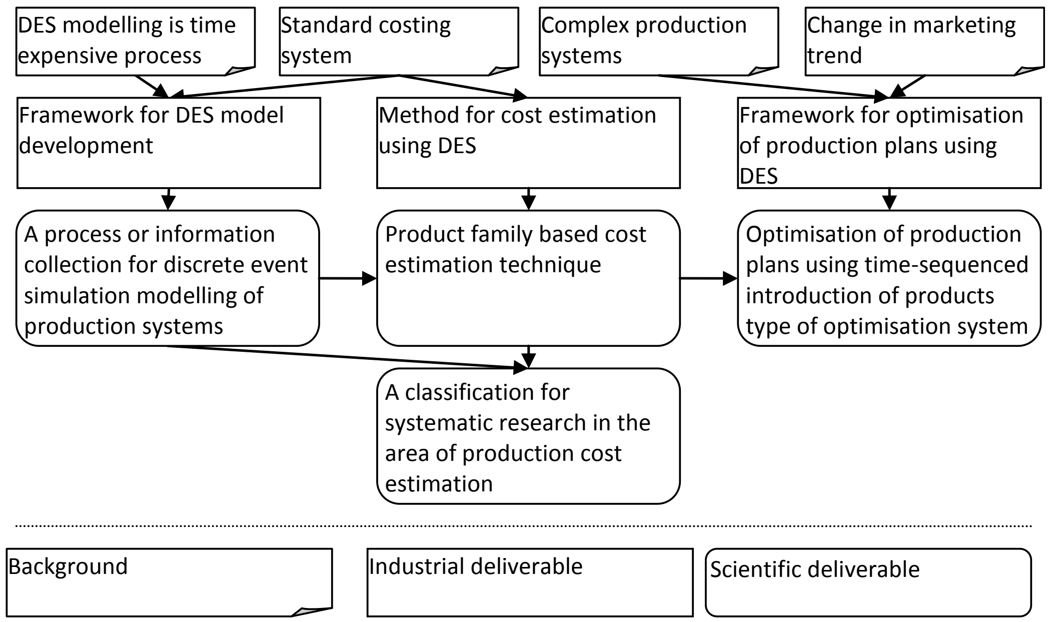


Figure 3.12: Developing frameworks.

A rationale for selecting every next objective is described in Figure 3.13. The analysis performed in Table 3.2 shows the capability of the research to influence and have impact to these concepts. For example, the researcher has no influence on a simulation engineer from Tata Steel Europe; however, the optimisation system or simulation models (being developed during this project) are likely to be affected by the researcher. This shows the potential focus in this real world research.

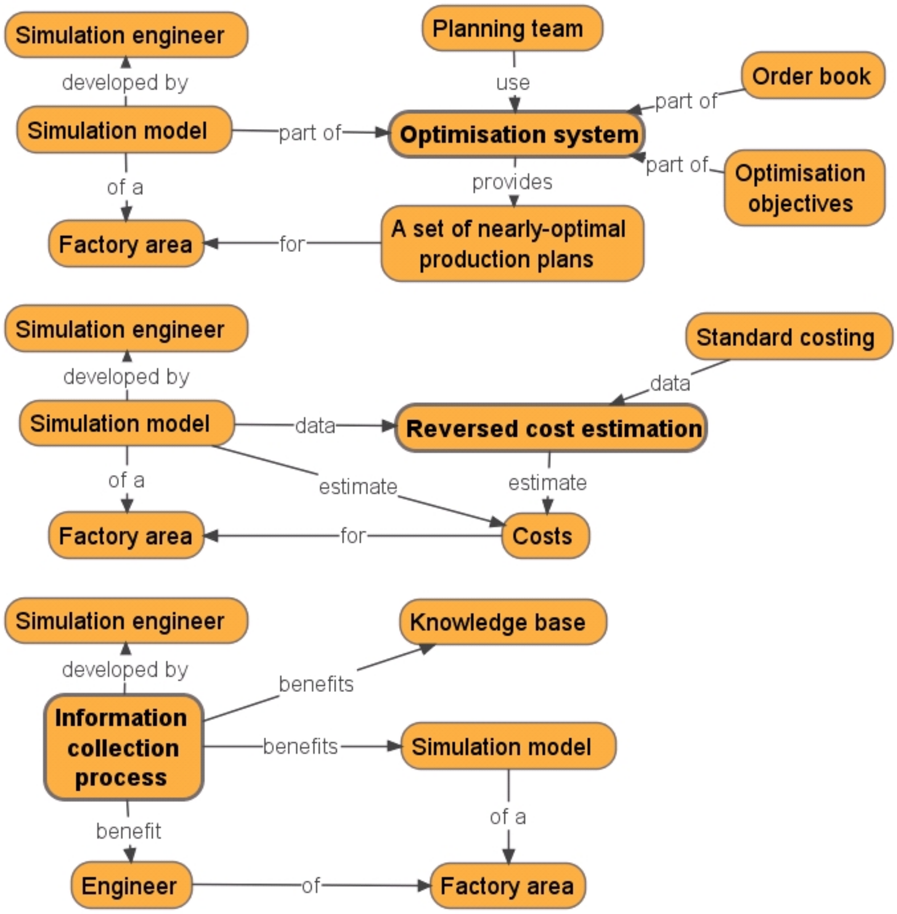


Figure 3.13: Objects and subjects that are related to the optimisation system, cost estimation technique and information collection process.

Belongs to	Concept	Influence
Optimisation system	Simulation engineer	Limited
	Simulation model	Possible
	Factory area	Limited
	Planning team	Limited
	Optimisation system	Possible
	Production plans	Limited
	Order book	Limited
	Objectives	Possible
Cost estimation technique	Simulation engineer	Limited
	Simulation model	Possible
	Factory area	Limited
	Reversed cost estimation	Possible
	Costs	Limited
	Standard costing	Limited
Information collection process	Simulation engineer	Limited
	The process	Possible
	Simulation model	Possible
	Factory area	Limited
	Experts	Limited
	Knowledge base	Possible

Table 3.2: Analysis of the concepts of the optimisation system, cost estimation process and information collection process regarding future research.

3.9 Summary

This chapter answers questions such as 'What is the focus of this research?', 'How this research was done?' and 'Why in this way?' A number of sub-sections provide the answers to these questions.

The chapter starts with the research aims and objectives. The objectives are formed from both the research gaps and the initial requirements mentioned in the proposal. The objectives are related to production planning & scheduling, production cost estimation, and the information collection for further development of discrete event simulation models capable of cost estimation (and being able to be used in production planning tasks). All of these objectives work towards one aim – a frameworks for steel manufacturing capability improvement using discrete event simulation.

A research strategy, a generic way to address these objectives, is described in the next section after the section on the research aims and objectives. The research strategy is defined and presented in a list of statements as follows. Taking initial agreements is a must. Validate objectives, actual research and research results. Describe the scope and its affect on the research. Make each of the objectives support other and work towards the aim.

Assessment of the research's scope via meta-analysis of the areas of subjectivity and objectivity, and definition of the major areas of subjectivity are described in next section. While this section does not provide answers to 'what and how' questions, it certainly provides answers to 'why' questions.

'How this research was done?' is answered in the few final sections (excluding the summary of this chapter). It incorporates the selection of research methods among many available, descriptions of research methods actually used, and the overall process of this research with the final bit of analysis on elements the researcher may influence; therefore worth researching.

Chapter 4

Current practices in steel making industry

4.1 Introduction

This chapter provides an overview of practices in steel making company related to production planning and scheduling, discrete event simulation modelling, and cost estimation.

4.1.1 Collecting information

The research focus is on how DES modelling affects the selection of research methods. Structured methods are not suited for the study of a small number of complex objects (*i.e.* DES modelling projects) especially in a multidisciplinary research such as this one. On the contrary, unstructured methods fit this situation well, because of the focus on information gathering from various information sources at every opportunity, regardless of a previously defined set of questions and sequence of actions. In this research, unstructured interviews and informal & participant observations are the main methods used in studying the organisation, definition of the research topics, and validation of the functional objectives.

Participant observation [152] is a method for data, information, and knowledge collection by playing a functional role in a real life, situation or project (see Section 3.6.3). The author has participated in a variety of projects in multiple business units, including a study of information systems, continuous improvement of production systems, and discrete event simulation modelling. This allowed to study the company in action, namely information and methods utilised by employees, their concerns and challenges and establish a broad knowledge-base.

This knowledge was extended with unstructured interviews, which is another method of collecting information. Prior interviews [152] have increased the interest of the researcher in research objects and helped in understanding the related system of concepts. It allows natural flow of conversation with people, related to his research object (see Section 3.6.4).

These methods form one of three foundations of the information collection, and answer the following question: 'How to collect the necessary information?' The focus of information collection – another foundation – is related to another question: 'What to look for during the study?' The third foundation – literature review – provides information on concepts, methods, and research trends; a significant part of the review is performed prior to the organisations study. Information collection is shown in Figure 4.1. Information is collected from multiple business units, employees and projects of Tata Steel Europe.

4.1.2 Business units and projects

The author studied production planning, cost estimation, and simulation modelling in a number of business units. A significant amount of information came from Tata Steel Research Development & Technology Business Unit in Rotherham, Tata Steel Europe Engineering Steels in Rotherham & Stocksbridge, and Tata Steel Europe Tubes in Corby. Other business units provide less information; among them there were Tata Steel Europe Strip Products in Llanwern, Tata Steel Research, Development & Technology in IJmuiden (Netherlands), and the production business unit in IJmuiden (Netherlands).

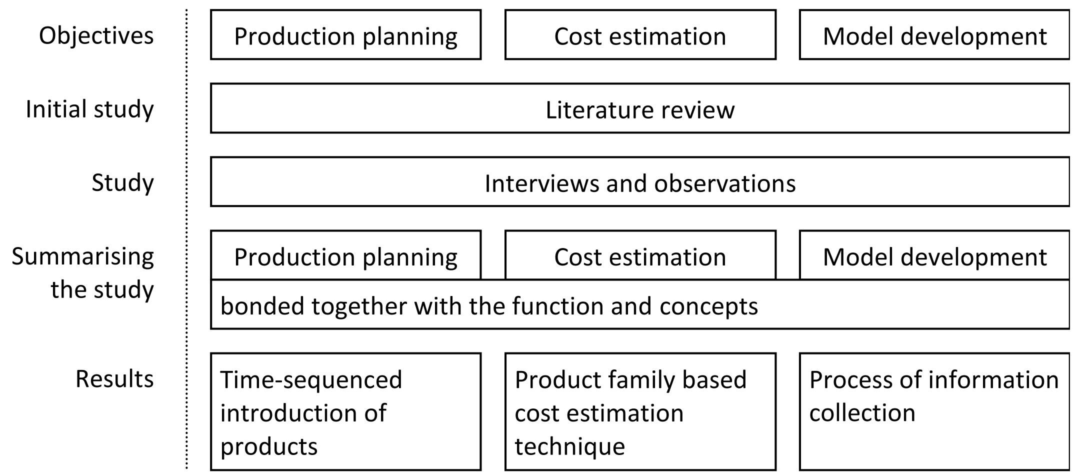


Figure 4.1: Overview of the study.

Business Units are interrelated organisations. For example, steel bars are produced in Tata Steel Europe Engineering Steels' facility (Rotherham, Stockbridge) and transported to Tata Steel Europe Strip Products (Llanwern) where it is reprocessed into rolled coil, which is further used by Tata Steel Europe Tubes (Corby). Some of the tubes' finishing operations are performed in Tata Steel Europe IJmuiden (Netherlands). These processes require well-developed transportation systems, both hardware (train, lorry or ship) and software.

The author has participated in a number of projects either related to production planning and cost estimation, manufacturing management and continuous improvement. Some of these projects took few months to complete while others were completed within few weeks. The projects with a significant amount of information are briefly described in Section 4.2. Some of these projects were selected for cases studies, the selection and subsequent use are described in Chapters 5, 6, and 7.

4.1.3 Employees and visits

The majority of Tata Steel Europe employees that were contacted by the author were working in simulation modelling, manufacturing, and production planning; however, specialists in IT, finance and logistics were contacted as well. Most of the people had more than five years of experience in the area, only two had less than two years of

Knowledge domain	Experience	Position	No of contacts
Simulation modelling	From one year to more than ten years	Specialists at junior and senior levels	Five
Manufacturing	From few years to more than ten years	From an experienced worker to a manufacturing manager	Six
Production planning	From few years to more than ten years	Specialists at junior and senior levels	Four
IT specialists	From few years to more than ten years	Specialists at junior and senior levels	Four
Finance and accounting	From few years to more than fifteen years	From low accountant position to finance director	Three
Logistics	From few years to more than fifteen years	Specialists at junior and senior levels	Two

Table 4.1: High-level overview of the contacts.

experience. Most of them were positioned on low and medium level of the organisation structure. These employees were working in different business units. The contacts are summarised in Table 4.1.

A guru on human intelligence, Dr. Howard Gardner, provides interpretation for the concept of 'expert' [159]: 'The terms expertise and expert are appropriately applicable only after an individual has worked for a decade or so within a domain. By this time, the individual will have mastered the skills and lore that are requisite to performance at the highest levels of their respective domain. However, there is no implication of originality, dedication, or passion in such a performance; expertise is better conceived with as a kind of technical excellence.'

The researcher was able to identify the following characteristics of the people: knowledge domain, years of experience, role/position, and number of people. Other information such as dedication, originality was unavailable for collection, while personal information such as name or contacts is not shared due data protection reasons.

Overall, 20 separate company visits were performed during this research (half of them were one-day visits). Separate indicates that these visits are different on business units, projects, purpose of the visit and/or contacted people. For example, a visit to attain a brief understanding of Ijmuiden's (Netherlands) production system and talk to a finance director is different from the first Fellowship in Manufacturing Management

(FMM) project in Tata Steel Europe Tubes, and the latter is also different from the second FMM project in Tata Steel Europe Tubes.

4.2 Projects

4.2.1 Information system of Engineering Steels.

In production business units, information systems share history of development with production systems. Business units have a broad variety of data platforms such as Oracle, IBM databases, and Microsoft Excel spreadsheets. Tata Steel Europe Engineering Steels is using BusinessObjects on top of that. Data from various information systems are transferred in a data warehouse. Further, these data are accessed via Business Universes; a Business Universe for a warehouse may serve as an example. Information reports are generated from one or many Business Universes. This information system, which is shown in Figure 4.2, contains over one hundred cost identifiers with repetitive naming, which sets an additional challenge for cost estimation.

Tata Steel Europe Engineering Steels were developing a sales and operations planning (S&OP) model to support the creation of robust manufacturing plans. A functional model and diagram for the data flow within this model are presented in Figure 4.3 and Figure 4.4. The idea for this software came from the specialists designing this sales and operations planning software. The author, after studying information systems in this business unit, developed this process (see Figure 4.4, which was further validated by the industry practitioners.

Data for this model should come from the information systems utilised by this business unit. However, these systems were developed during the previous forty years of operation and have a number of information items sharing similar names; for example, these information systems have over one hundred types of costs. The author's task was to propose a set of concepts to use in the sales and operations planning model. Understanding the basis of information systems in Tata Steel Europe was the major informative outcome for this research. It was decided to create the new software solution with no constraints in regards to the implementation techniques. Mixed architecture,

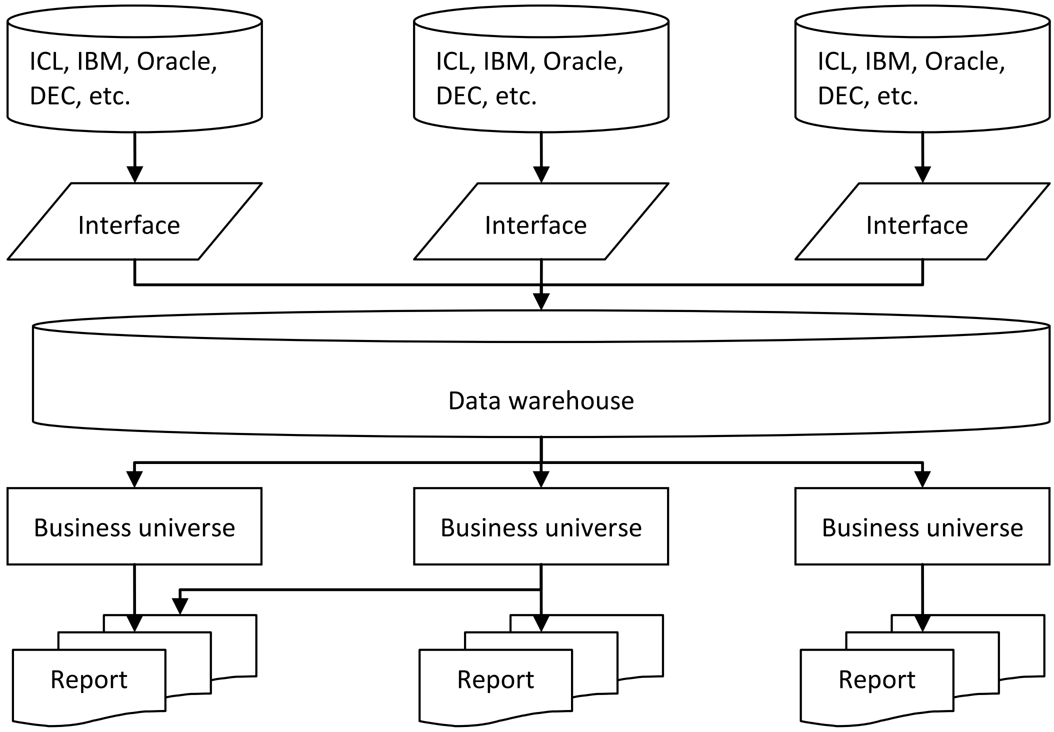


Figure 4.2: Information system structure in Engineering Steels.

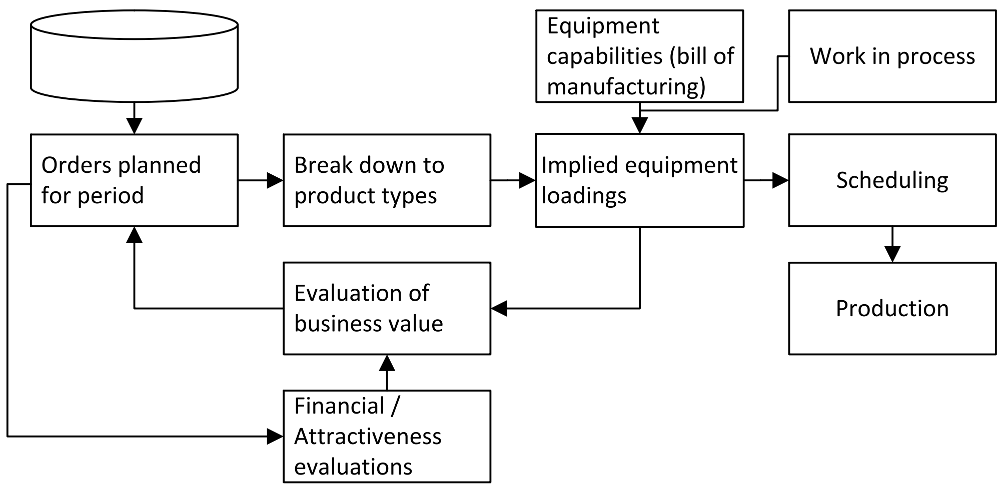


Figure 4.3: Overview of S&OP model process.

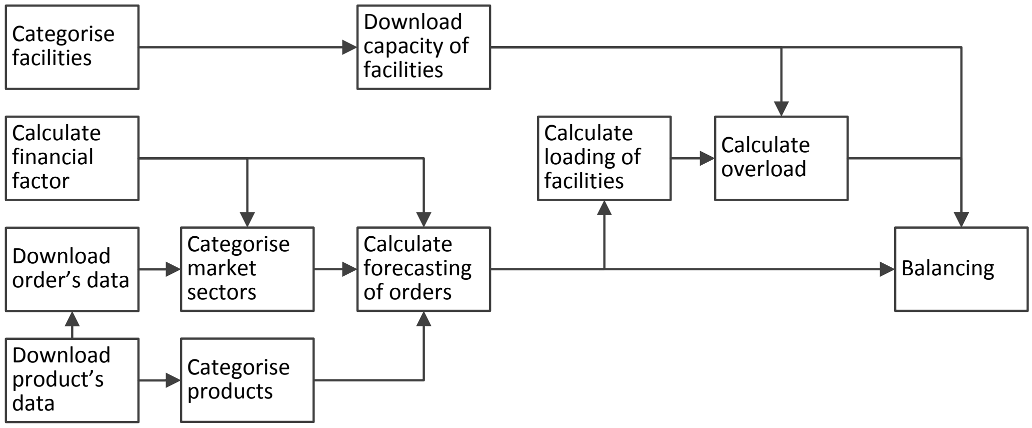


Figure 4.4: Simplified data flow diagram of S&OP model.

department-based information systems, and umbrella software were likely candidate solutions having been already deployed in the company. However, the researcher was able to use any technology while developing a software prototype for validating research hypotheses. Some of the outcomes from this project are presented in Figure 4.2 and Figure 4.5.

4.2.2 Fellowship in Manufacturing Management projects.

Cranfield University received Queen's Anniversary Prize for its Fellowship in Manufacturing Management (FMM) programme in the year 2005. One third of this program is based on a series of two-day long manufacturing management consultancy projects done by groups of two to three people. The author participated in three projects consulting Tata Steel Europe Tubes on installation of new equipment, improving throughput, and analysing internal logistics systems. The author worked with four people: with one in the first and second project, and with two in the third project.

Any location consists of multiple production areas each managed with separate shop floor managers trying to meet individual production plans. Even with years, in many cases decades of experience, teams often work on a fire-fighting basis. There still is room for improvement in production operations.

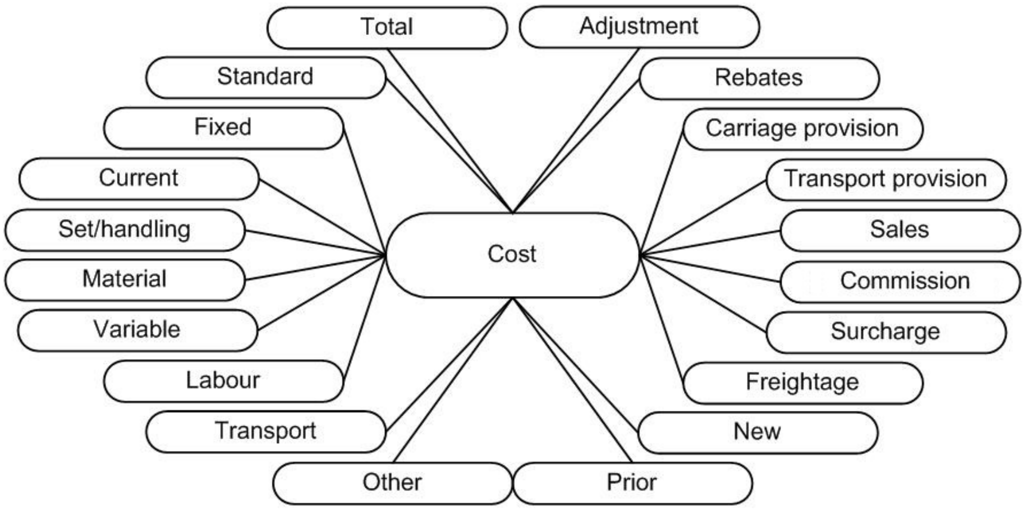


Figure 4.5: Cost types in use in Engineering Steels.

All the projects provide industrial practice for methods FMM people were thought previously in this course. Those include *Newman's wheel*, which is a structured approach for project management and an expansion on the simplified Plan, Do, Check, Act cycle commonly known as the *Deming cycle*. The second method, or rather a collection of manufacturing practices, called *lean manufacturing*; three projects provide an opportunity for Green Belt qualification in lean manufacturing.

Understanding the manufacturing and production planning environment in Tata Steel Europe was the major informative outcome for this research. In addition to this, the author was introduced to techniques useful for continuous improvement of manufacturing processes. The outcomes from these projects are a joint result of the FMM people, specialists from the business unit, and the author. These short projects helped in the initiation of two MSc and one PhD project, as well as the project described in Section 4.2.3 which is the only project used as case study in Chapters 5, 6, and 7.

4.2.2.1 Assessment of a new production area

The assessment of production capacities of a new production area in Tata Steel Europe Tubes was the purpose of the first project. This area consists of two machines and three buffers; it has four input sources of products and two output destinations. The

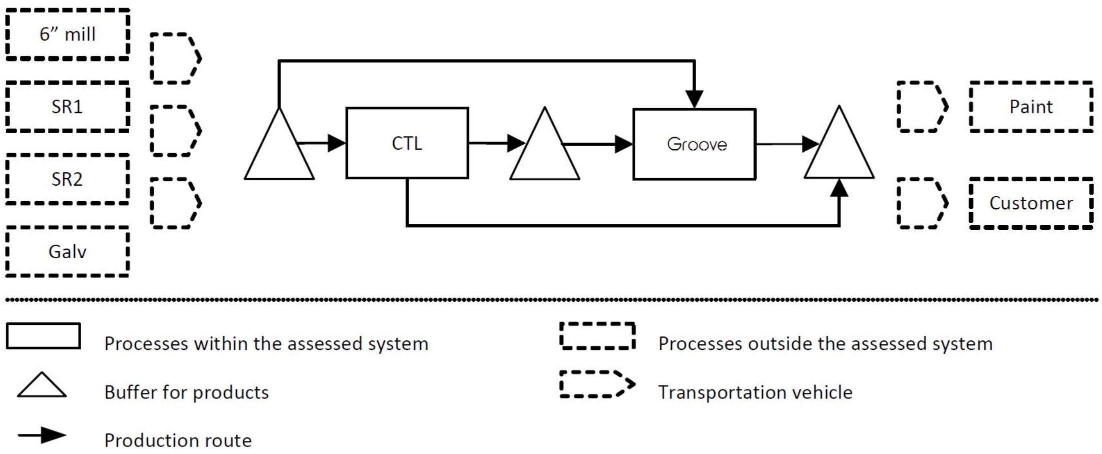


Figure 4.6: A schematics of new production facility that consists of Cut-to-length (CTL) and grooving machines and three buffers.

schematics of the production area is shown in Figure 4.6. Two methods of assessment – through a capacity calculator and manual simulation are described below.

Capacity calculator was developed by the author as a MS Excel-based tool. As input, it takes production capacities of machines and yearly production plan for the year 2007, production routs and products; this information is shown in the top part of Figure 4.7. Output of this tool is an estimation of the production area's capacity on a weekly basis as is displayed in the bottom part of Figure 4.7.

A manual 'brownpaper' simulation was performed to assess the dynamics of the production system. A joint team of FMM people, operation and manufacturing managers, production planning and continuous improvement representatives run the simulation. The top part of Figure 4.8 presents both the tool and some people involved; while the bottom part shows accumulated buffers. The most valuable one is that at the end of every second week, the output buffer collects around 1400 tonnes of steel products.

This FMM project proved that the new production area is capable of handling the expected production flow. In addition to that, some recommendations were listed for improvement of the production area.

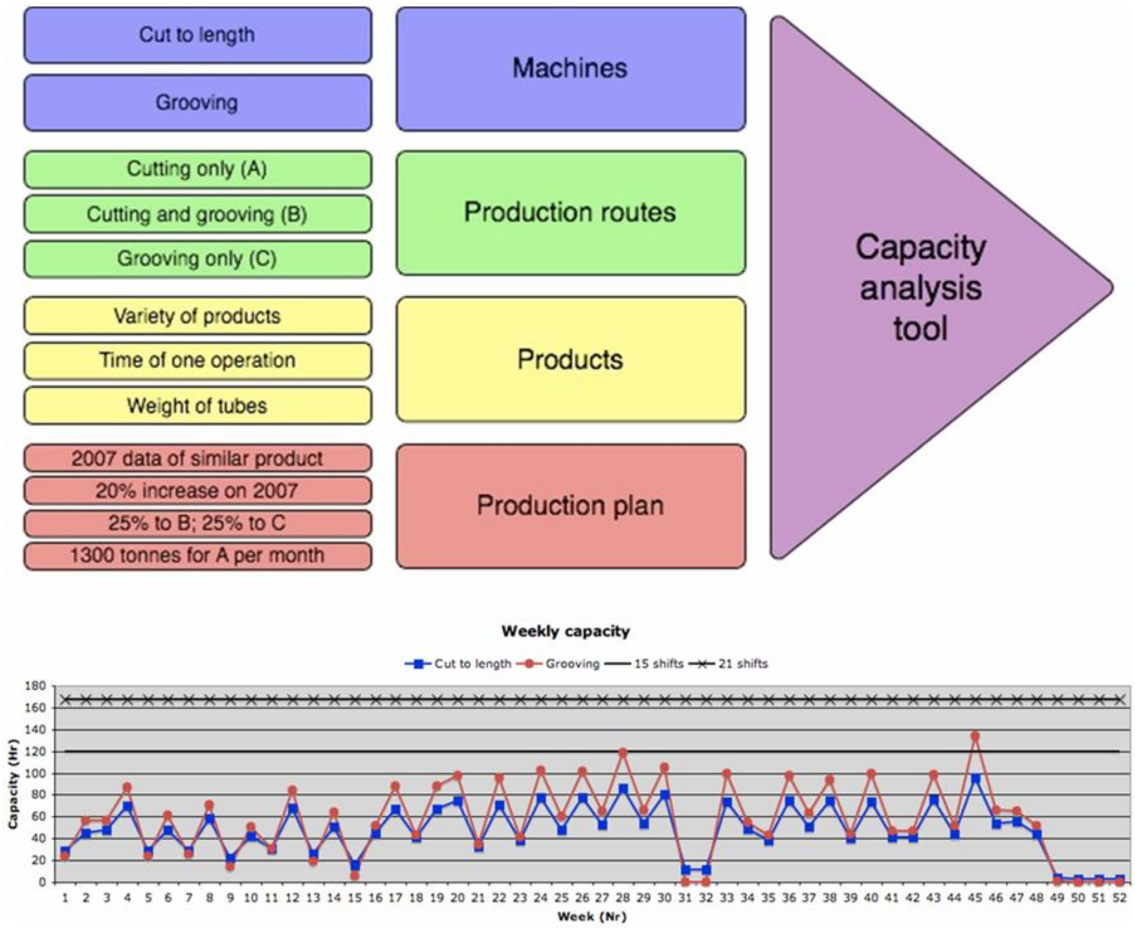


Figure 4.7: Input and output of the capacity analysis tool.

4.2.2.2 Internal transportation system

The second FMM project aimed to identify issues with Road Transportation System (RTS) units in order to create a smooth production flow within the plant; the map of this plant and photo of RTS units are provided in Figure 4.9. The specific objectives for the project are listed as follows: deliver a current state peak flow map for RTS units, identify how orders are scheduled, identify risks in the current process, identify any non-value adding activity, and provide a roadmap of how to move between the current and ideal states. As in the previous project, Newman's wheel and lean manufacturing were utilised.

The focus of this project was RTS units, a massive yet relatively simple piece of engineering. It has no engine and is moved with one of three tugs, one unit transports 30 tonnes of steel tubes on average, and 34 units transport 5000 tonnes per week.

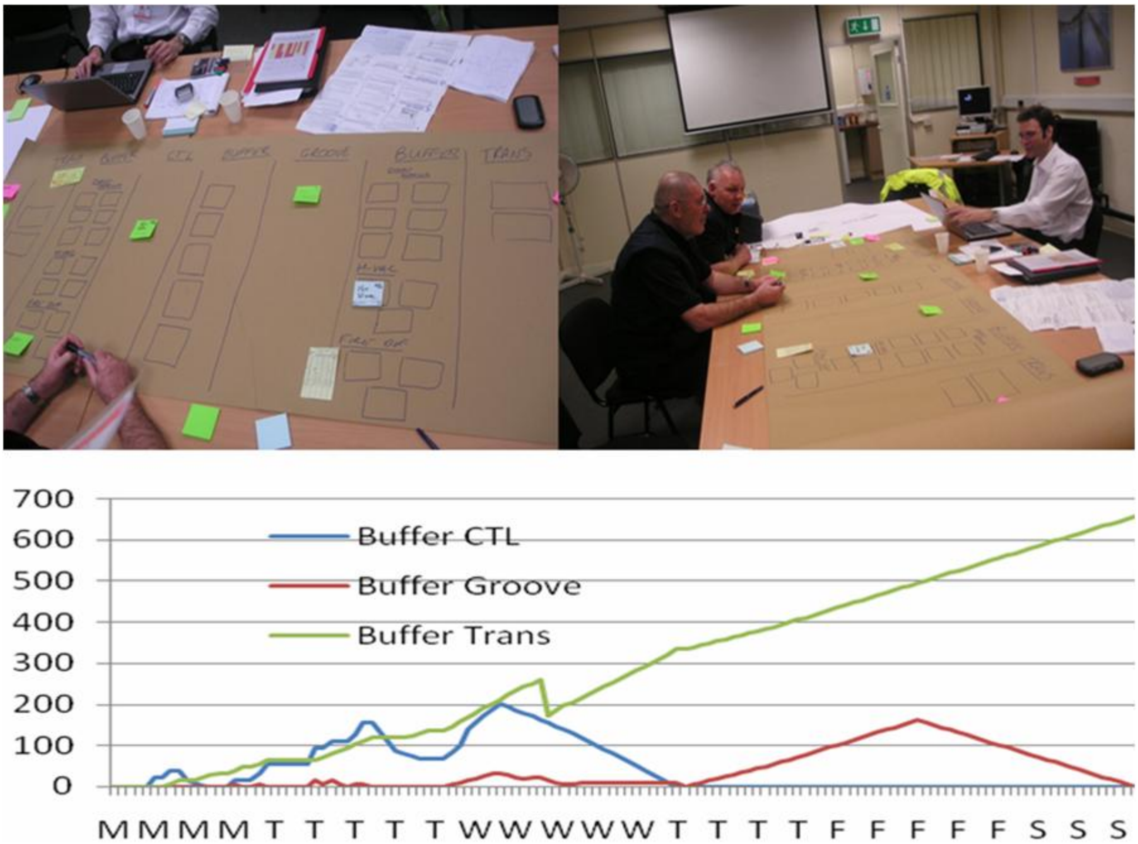


Figure 4.8: Manual simulation.

Each product takes 3 to 7 transportations on average. Transportation includes requests for tugs and units, waiting and actual transportation, loading and unloading. Other transportation devices, *i.e.* conveyors, cranes and shop lifters were out of the focus of this research as this transportation equipment is mostly used within production bays. A transportation system is presented in Figure 4.10.

The author developed RTS movement analysis tool that is capable of calculating a number of RTS movements and transportation time. This information is useful for planning and shift coordinators and could be used in weekly meetings and daily team briefings. Planning and shift coordinators would test different scenarios using this tool. Figure 4.11 shows components of RTS movement analysis tool as well as providing sample results.

A team of a dozen specialists on manufacturing, continuous improvement, logistics, workers, project and purchasing managers named the problematic issues with the

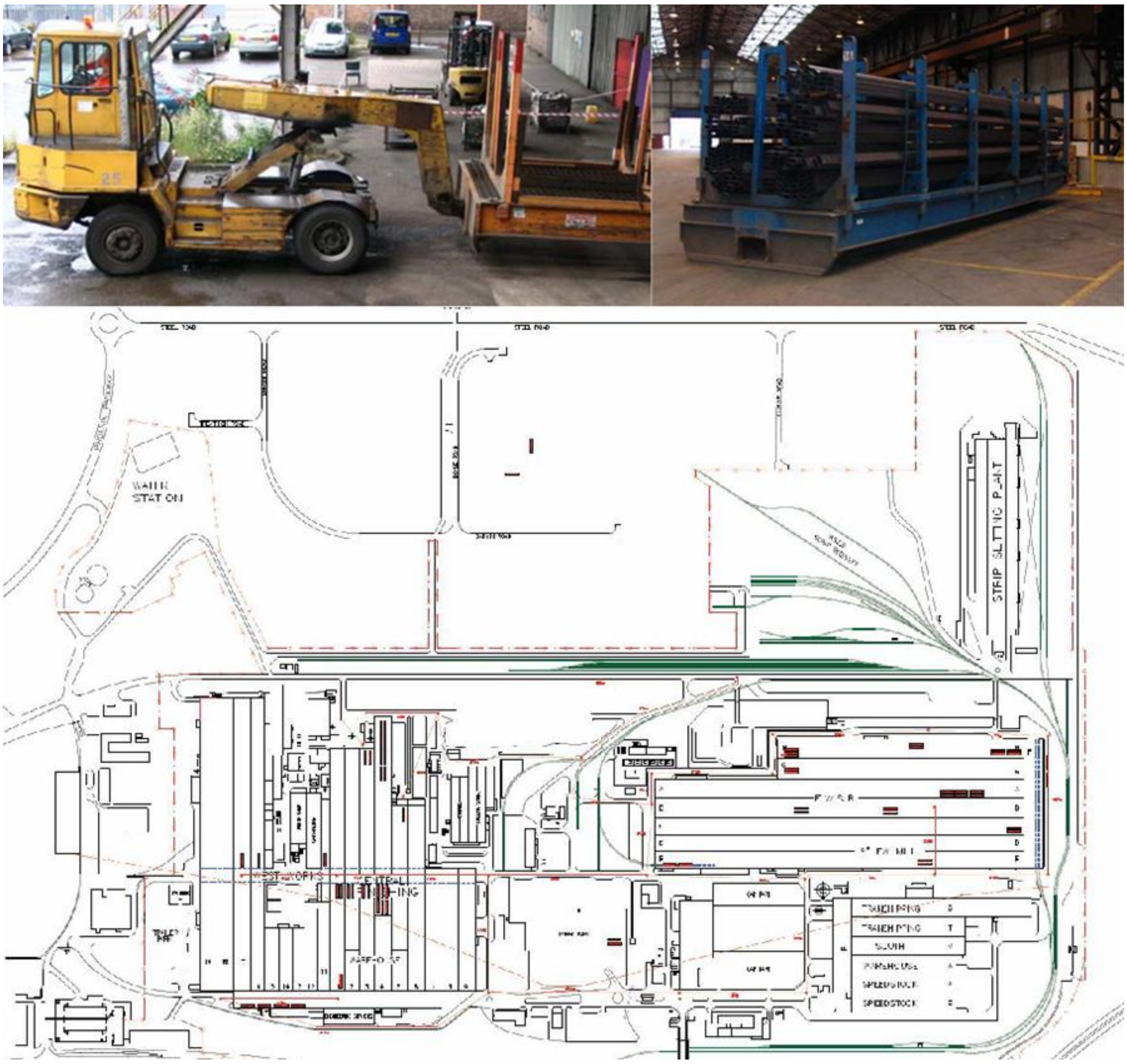


Figure 4.9: A tug that drive RTS units through the plant.

transportation system. These issues were grouped into four; including resource, communication, process, and planning issues as it shown in Figure 4.12.

The team generated 16 recommendations for improvement, and by a time basis the recommendations were divided into three groups consisting of short term (within 4 weeks, 8 recommendations), mid-term (within 6 months, 4 recommendations) and long term (by the end of 2008 [The project run during 11 – 12 March 2008], 4 recommendations). The recommendations were also analysed with Ease-Effect rating table which is displayed with Table 4.2, such as investigate whether it is useful to use MSAC area

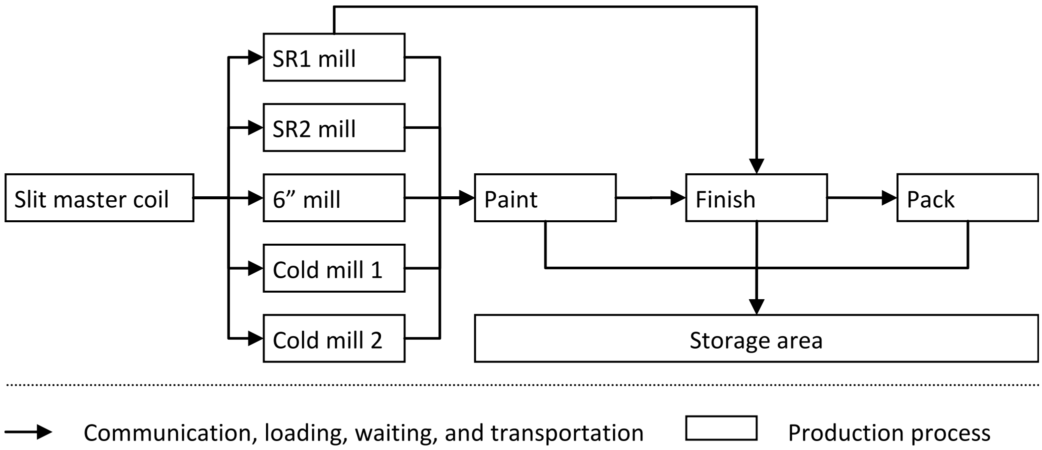
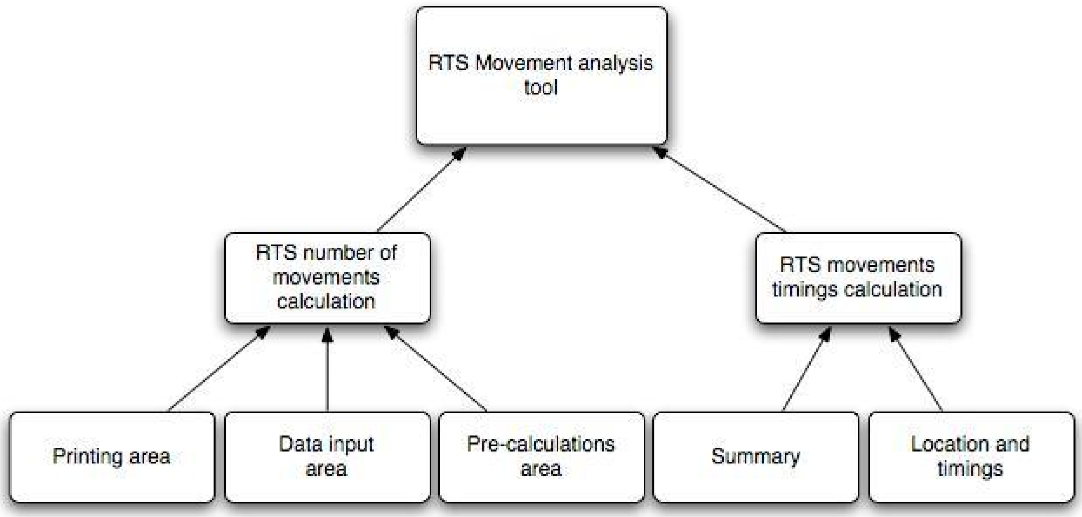


Figure 4.10: Major production flows supported by tugs & RTS units.



From-To	SR1	SR2	6"	SR FL	CF	Paint	CF1	CF2	SW	LCD	CDT
SR1				?	?						
SR2				?	?	?					
6"		?	?		?	?				?	
SR FL					?	?				?	
CF			6.667	0	2.667	6.667				0	4
Paint					12.5						
CF1									?		
CF2					?				?		
SW											
LCD					?						
CDT											

Figure 4.11: RTS movement analysis tool: tool components and RTS movement time between different locations of one scenario.

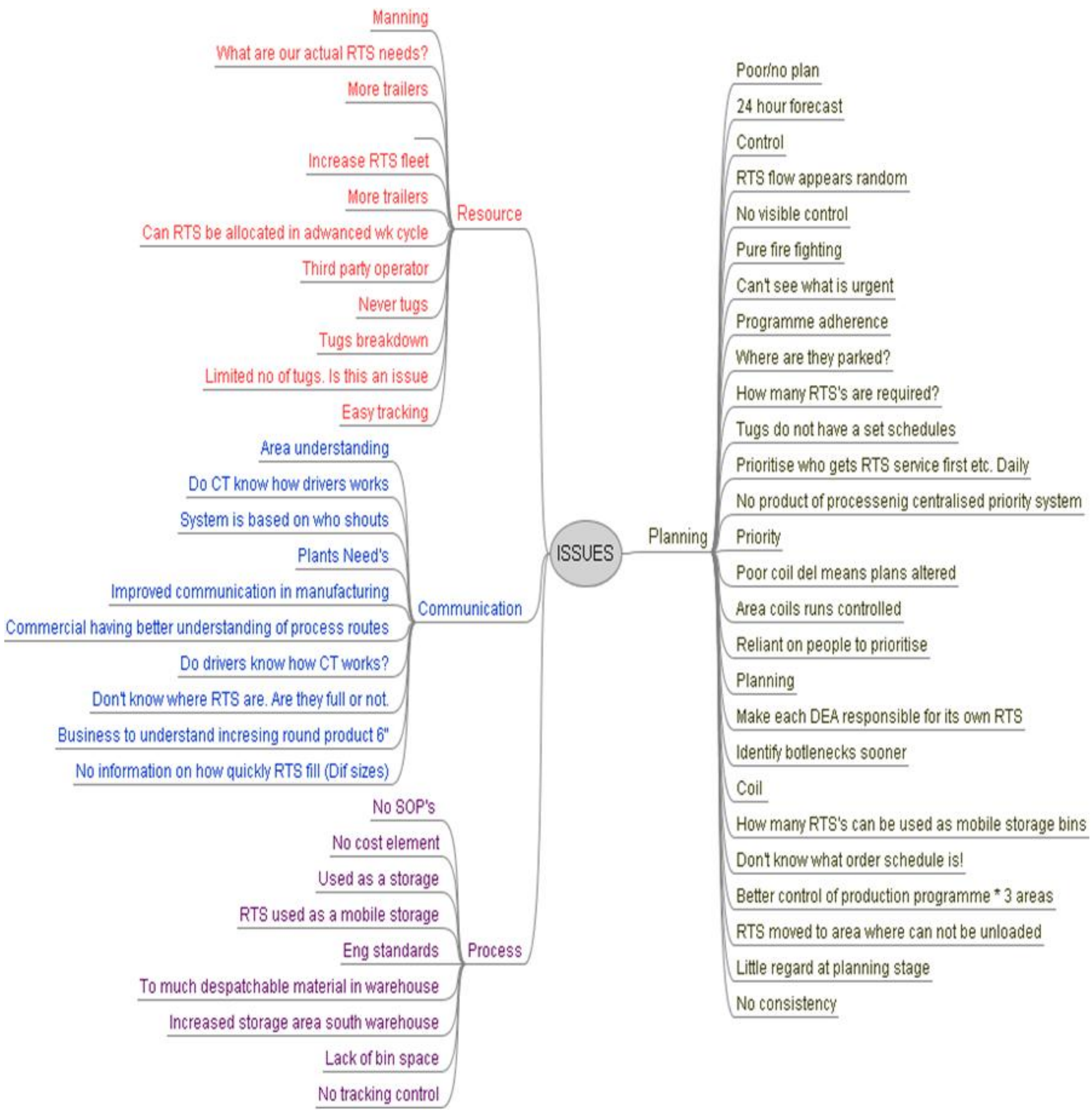


Figure 4.12: Four groups of issues.

for storage, make service-level agreements (SLA) for third party operators, and fix the main bottleneck in RHS Flow line.

The representative from FMM and the author led the issue gathering and further analysed the issues. This is a joint effort project, the author gained more knowledge about steel manufacturing, continuous improvement, and group work. This FMM project continued in a MSc project described in Section 4.2.4.1.

Description	Ease	Effect
Weekly planning meetings	Easy	High
Daily briefings	Easy	High
Dect phones	Easy	High
Contact information to be circulated	Easy	High
Investigate the availability of the MSAC area	Easy	High
Initiate reporting of all traffic issues	Easy	High
Set min/max levels - raw material/WIP buffers	Easy	High
Data capture with RTS movement analysis tool.	Easy	High
Data capture for the Tandem project pilot.	Easy	High
Use info from data capture exercises to set max level for RTS units by area	Easy	High
Set turnaround times for RTS unit by area	Easy	High
Appoint coordinator to manage the resource.	Moderate	High
Tandem pilot	Moderate	Low
Tandem rollout	Hard	High
Training & Development	Hard	High
Standard operational procedures	Moderate	High
SLAs for internal departments	Moderate	Low
SLAs for third party operators	Moderate	Medium
Move of the paint line to Central Finishing	Hard	High
Movement of the RHS line to the mills	Hard	High

Table 4.2: Ease-effect rating table for recommendations.

4.2.2.3 A crucial production area

The final and third FMM project in Tata Steel Europe aimed to provide recommendations for improvement of small production area, namely Bay 4 and 5. The objectives were stated so as to deliver the current state for Bays 4 and 5 in Central Finishing area, with opportunities for improvement including any efficient throughput and financial benefits, deliver a future state, and provide a detailed roadmap with time scales in the recommendations. As the previous projects, it was two days long and utilised the same methods: Newman's wheel, lean manufacturing, and theory of constraints (TOC).

The production areas were studied with the help of manufacturing and planning people. The current state was recorded in a form of a flow chart, both Bay 4 and 5 are described in Figure 4.13. Some processes are stated as critical (see TOC developed by Goldratt [156]).

According to TOC, a key for improvement of a manufacturing system is a constraint in a process – an operation that takes the longest to process (or is the busiest, or both).

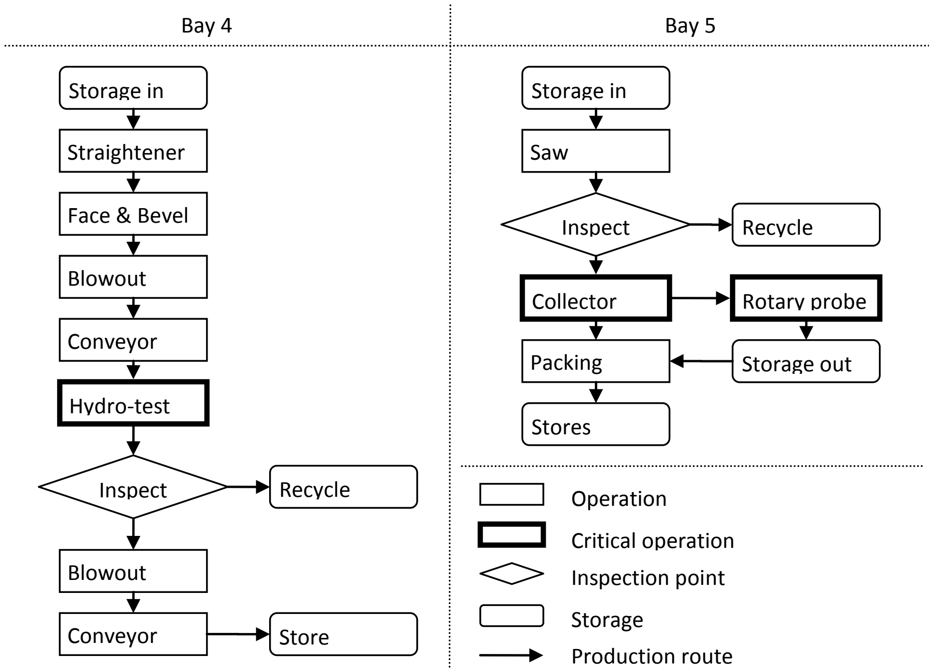


Figure 4.13: Current state of Bay 4 and 5.

Therefore, the search for recommendations has to be focused on dissolving the identified constraints. The recommended actions to improve Bay 4 and 5 are listed in Table 4.3.

Though one recommendation is worthy of a separate description. The team found that a simple installation in Bay 5 – a loading table – would allow parallel processing of one of the major products while keeping the rest of the Bay 5 occupied with other products. This change and possible outcome is displayed on Figure 4.14.

The FMM representatives and the author gathered information and mapped the production processes. Working together with the specialists from the business unit, they analysed the current and proposed processes. This was a joint effort project. This project led to the subsequent project described in Section 4.2.3, which was used as case study in Chapters 5, 6, and 7. The author gained more knowledge about steel manufacturing, continuous improvement, and group work as well as understanding that a simple change may significantly benefit the client and that bias may prevent the specialists from seeing this simple change.

Bay 4: hydro-test	Bay 5: Saw & rotary, probe	Timescale	Impact
Pressure Sensors Manning Review	Table Tube Identification Manning Review Resource Optimise	4 weeks	Direct Capacity Flow
Bay layout Stock Management	Training	3 months	Direct Capacity Flow
Storage Automation Auto Cranes	Storage Automation Auto Cranes	>6 months	

Table 4.3: Recommended actions to improve Bay 4 and 5.

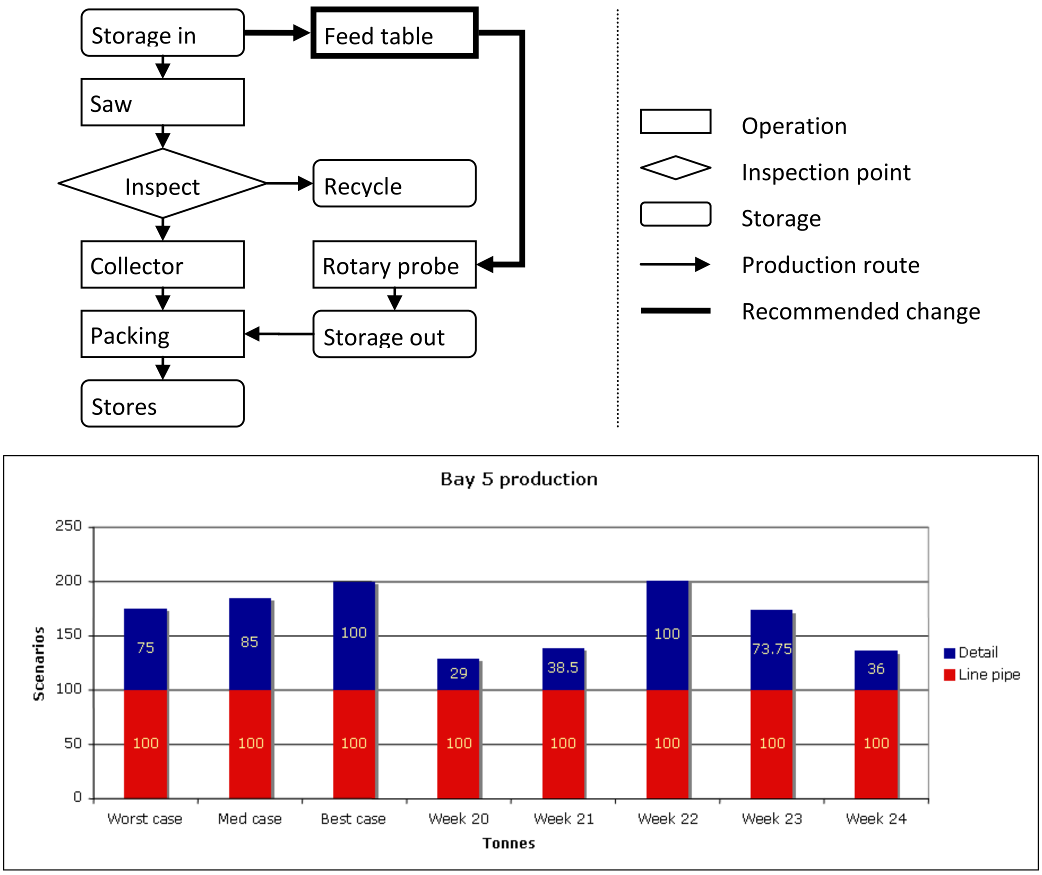


Figure 4.14: The recommended future state of Bay 5, and possible outcome of this change is shown with red colour – 100 additional tonnes a week.

4.2.3 Tata Steel Europe Tubes Bay 4 simulation modelling

Tata Steel Europe Tubes started development of a new operation management system. One of the core technologies of this project is discrete event simulation modelling, and such DES models were developed for the major part of production system. The author developed the simulation model of Bay 4 production area.

The simulation model was developed using the information collection process – one of the research contributions of this project; this process is described in detail in Chapter 7. It starts with identification of meta-data, such as objectives and information sources. Information collection on the major elements of production system – machines, products, stores, transporters, and resources is the next stage of the process; all information was successfully collected during one day of informal interviews with a number of experts of this production area. Development of conceptual and DES models are the next stages of this process.

Bay 4 is a semi-linear production system that consists of eight elements; it has two entries into the actual production, however, no parallel processing is possible. Products may be processed by more than one machine, and are grouped into product families on the basis of the utilised machines. Products are moved by a crane, which loads and unloads tubes from RTS units and buffers, and built-in conveyor that transports products between machines; if a machine is not utilised then a product moves through a machine without any operation. All machines have their own processing time that depend on the product characteristics, such as tube diameter and gauge. Figure 4.15 is the map of Bay 4, while Figure 4.16 shows Arena simulation part of this model.

This model is used most often in this research. It has been developed by following the information collection process; and the success in development partially validates the process. Due to the lack of cost information, this model was not used for direct cost estimation; however, this model was used as an example for the reversed one, product family based cost estimation technique, see Chapter 6. Finally, this model was also used as the first case study in the optimisation part of this research. All these cases are discussed in more detail in the following chapters.

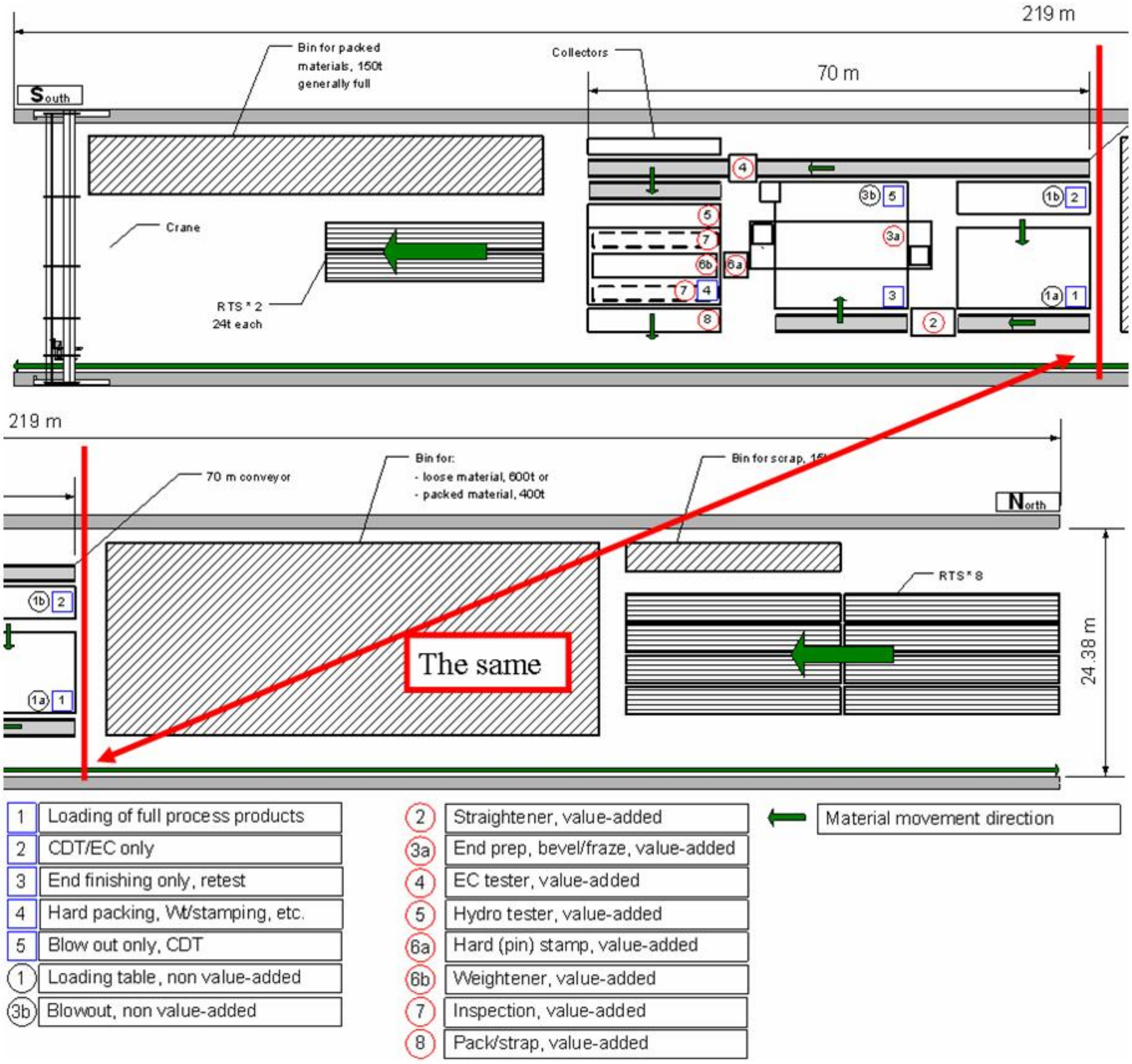


Figure 4.15: The map of Bay 4.

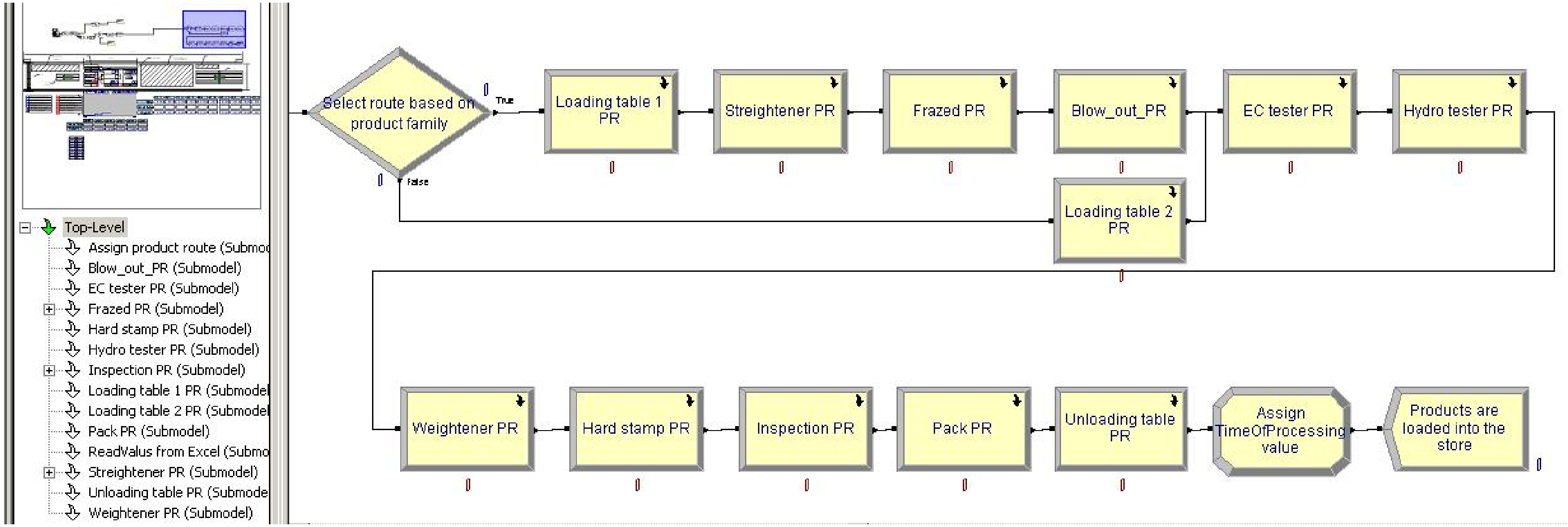


Figure 4.16: Bay 4 simulation model.

4.2.4 MSc projects

Cranfield University supported Tata Steel Europe Tubes with analysis of the packaging area and internal logistics system. Two MSc students had three months to develop simulation models, run experiments, and provide reports both to the university and to the company. Having understanding of the industrial and academia environment, the author provided support to these MSc students regarding DES modelling, steel manufacturing in this business unit, and contacts with the company. Understanding of simulation modelling and manufacturing environment was the major informative outcome from these projects; these projects were also used in validation of the process of information collection as described in Chapter 7.

4.2.4.1 Internal transportation system

Tata Steel Europe Tubes were facing challenges in the coordination of logistics tasks. This project [160] aimed to define logistics tasks within the company and provide a state-of-the-art review regarding the logistics. The objectives of this project include literature review, mapping of production routes, bottleneck identification of logistics scheduling, and recommend potential improvements.

Internal transportation system consists of a logistics coordinator that manages movement of three tugs and thirty-four road transportation (RTS) units; excluding a coordinator, these elements are presented in Figure 4.9. A logistics coordinator collects requests from the job shop coordinators and, frequently on a fire-fighting basis, makes logistics decisions. Tata Steel Europe Tubes outsource the logistic coordination to another company.

A simulation model that represents transportation within few production routes was developed; a flowchart of RTS movements is shown in Figure 4.19, while the production process is described in Figure 4.20.

The simulation model was used to run three scenarios. The first scenario represents the system having three tugs and twelve RTSs, the second scenario incorporated a potential breakdown of tugs, while the third scenario focused on reducing available resources, yet having the same level of production flow.

Figure 4.17: Three types of storage and a side-loader.

4.2.4.2 Packaging

This MSc project [161] ran in parallel with the previous one, with the focus to study the storage area of Tata Steel Europe Tubes. This project aimed to test various packaging techniques using a simulation model of the storage area. The objectives include development of a simulation model of the area, scenario design and experiment, and development of generic solutions.

Tata Steel Europe Tubes has a large storage area for orders awaiting dispatch. The orders include tubes of different size, shape, and properties – are stored in either one or two tonnes bundles. These packs are stored in racks or bins or on the floor, and are lifted with a side lifter, see Figure 4.17.

The storage area has a capacity of 1000 tonnes in bins, 5000 in racks and 2500 on the floor. The personnel developed a variety of rules regarding storage of different types

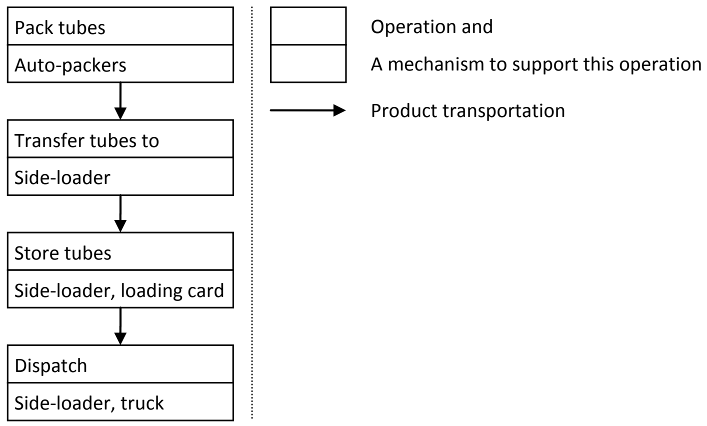


Figure 4.18: Operations in the storage area, [161].

Experiment	Bundle size	No of side-loaders	Special conditions
0	2	2	No
1	1	2	No
2	2	2 & +1 for PS area only	No
3	2	2 & +1 for PS area only	An order of 420 tonnes
4	2	3	No
5	2	3	An order of 420 tonnes
6	2	4	No
7	2	4	An order of 420 tonnes
8	2	2 & +1 for PS area only	544 to store and 420 bundles to dispatch
9	2	3	544 to store and 420 bundles to dispatch
10	2	4	544 to store and 420 bundles to dispatch

Table 4.4: The difference between the eleven scenarios, [161].

of products and orders; these rules were kept simple for this study (for two products only). It has to be noted however that the capacity is different for one or two ton bundles. The storage area has four major types of operations; these operations are introduced in Figure 4.18.

The students ran eleven scenarios, the critical information about these scenarios is stored in Table 4.4. It appears that the store requires additional resources, specifically, an additional side-loader that serve both packaging (PS) and dispatching (SD) sides of the store.

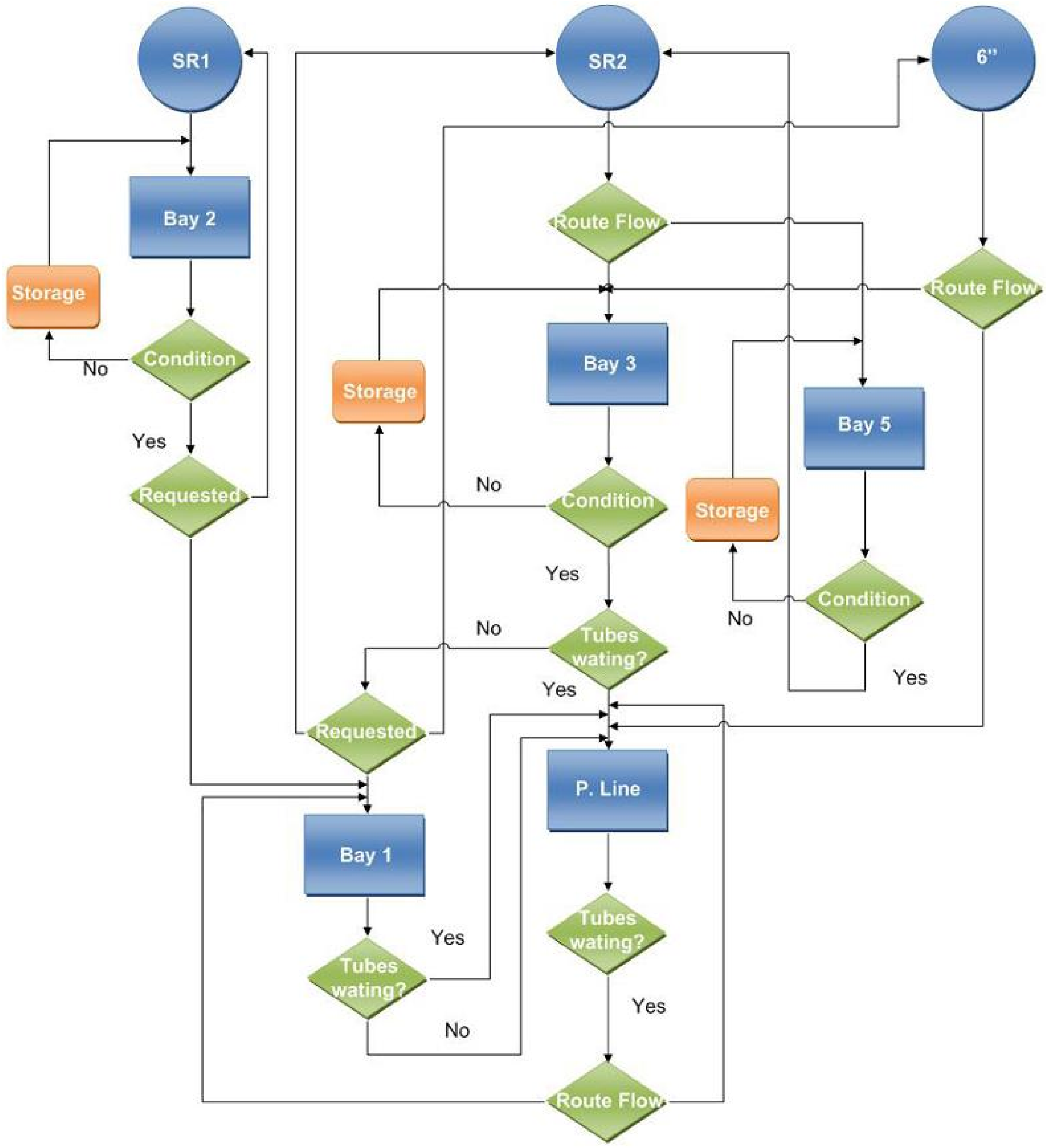


Figure 4.19: Tata Steel Europe Tubes RTS flowchart, [160].

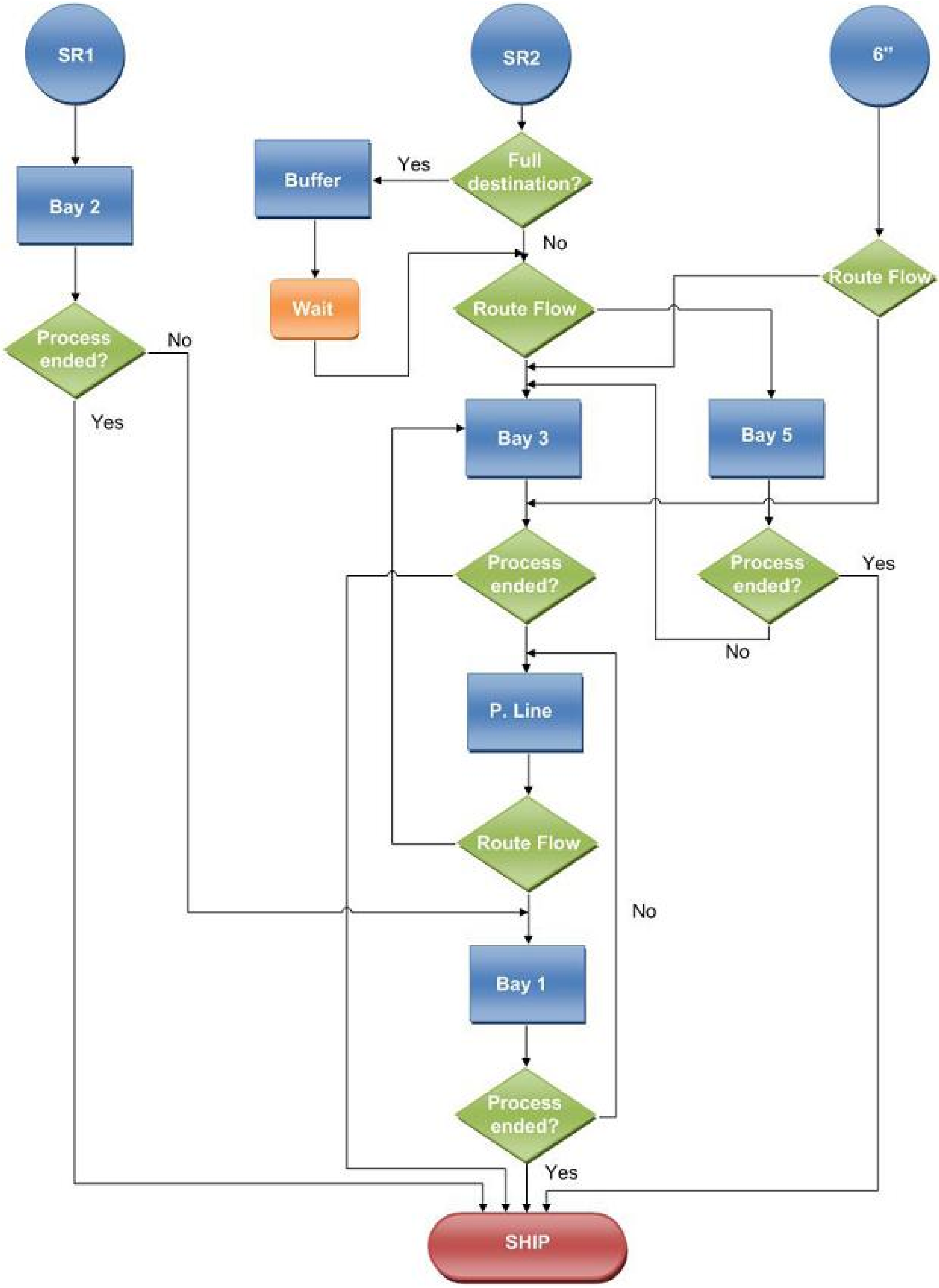


Figure 4.20: Tata Steel Europe Tubes flowchart, [160].

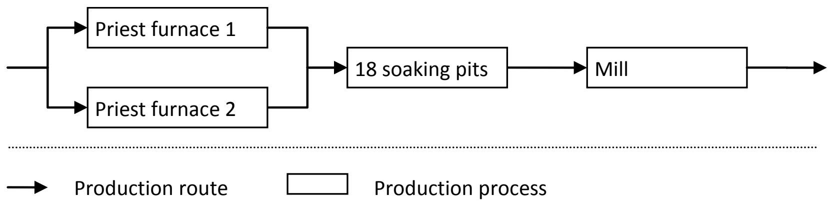


Figure 4.21: Heating End of Stocksbridge mill.

4.2.5 Heating End of Stocksbridge mill

This project, developed by simulation modelling specialists of Tata Steel Europe, was studied and further used as a case study in the optimisation part of this research. The simulation model represents one production area in Tata Steel Europe Engineering Steels. Investigation of continuous working on a 24*5, a total of 120 hours, was the original objective of this project. Later, this objective expanded with an experiment in which either production of 8600 tonnes can be achieved or not; experiments showed that it can be achieved within 131 hours.

This area consists of two pre-heating furnaces, a number of soaking pits and one mill excluding two cranes and charge units. These machines form a semi-sequential production process with two product entry and exit points. External logistics is modelled with an entity generator while internal logistics is represented with cranes. A simplified production process is provided in Figure 4.21.

4.2.6 Shotton simulation model

This project, developed by simulation modelling specialists of Tata Steel Europe, was studied and further used as a case study in the optimisation part of this research. The simulation model represents a production system of Tata Steel Europe Colours. The project aimed for improvement of supply chain, production planning and scheduling process. The proposed system configuration is described in Figure 4.22.

This area consists of a number of production bays, buffers, external and internal transportation systems. This model represents the whole plant that receives steel from

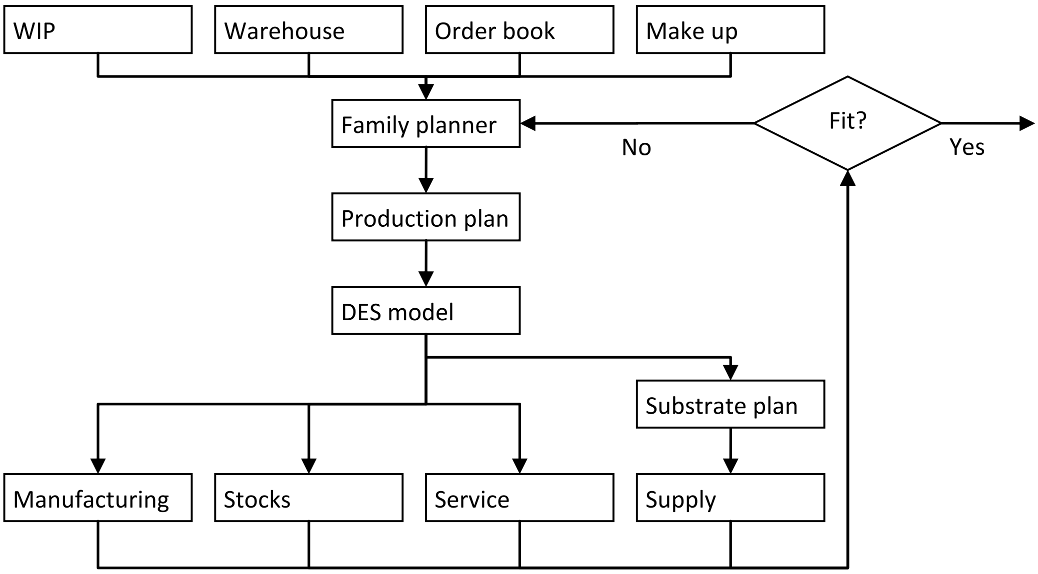


Figure 4.22: Proposed system configuration.

two other Tata Steel Europe locations, based at Port Talbot and Llanwern. A simplified production process is shown in Figure 4.23.

4.3 Production planning

Tata Steel Europe is a company with many production facilities. Before being merged into one enterprise, each of these facilities was a separate company (mostly focused on a specific type of steel product, such as steel bars, coils, or tubes). This specialisation carries over to company policies regarding production planning; each of the production facilities has own production planning and scheduling system. Obviously, while there are differences due to production specifics and historical preferences, there are also general similarities, such as sales departments to fill in the order books, production fulfils these orders, and dispatching sends these orders to customers.

The researcher participated in a number of projects – S&OP (Section 4.2.1), Bay 4 model, a part of a bigger project (Section 4.2.3), Heating end model (Section 4.2.5) and Shotton model (Section 4.2.6) – that directly or indirectly related to improvement

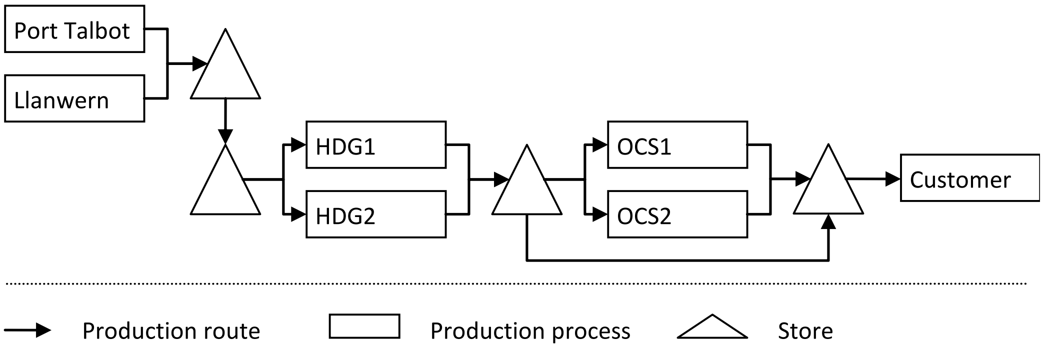


Figure 4.23: Simplified production process in Tata Steel Europe Colours.

of production planning and scheduling. All these projects, except S&OP (Section 4.2.1), utilise discrete event simulation modelling for production planning and scheduling.

Therefore, some production facilities of Tata Steel Europe make individual attempts to improve their production planning and scheduling (PPS) systems. In particular, their interests and needs are big enough to trigger the improvement projects. In a number of attempts to improve PPS, DES was used as a technique that allows modelling of complex stochastic and dynamic systems.

A number of challenges in production planning were identified during the study of production planning and scheduling. Change of marketing trend from a small number of large volume orders to a big number of small volume orders is one of them. Lack of communication between sales, production, and planning departments is another one. The experts mentioned that current production planning and scheduling practices are biased and that the planners lack confidence in the optimality of their production plans. Solution development becomes more complicated by considering size and long life cycle of production equipment; it is difficult and expensive to reallocate.

The change of marketing trend from a small number of large volume orders to a big number of small volume orders provide regular challenges to production planning and operational management, put pressure into internal logistics system, and significantly increase stock of products in warehouses. In addition to this, a weak connection between sales and manufacturing leads to contracts which are difficult to fulfil in time. That often results in delayed orders and orders formed from less urgent orders which often cause changes in production schedules.

Tata Steel Europe Tubes is interested in information systems that would allow sales to oversee the impact of an order to a production plan. Production planning is interested in an information system that allows testing of alternative scenarios. In addition to this, they are interested in automatic design of optimal production schedules and plans, as they do not have the knowledge that their production plans are optimal.

The major concern of Tata Steel Europe Engineering Steel was the need for an information system supporting development of robust manufacturing plans. This information system should work on real data of capacity in certain areas, and propose production plans fitting the available capacity. For example, in the event of no capacity indicated by the information system (for the time period under consideration), some orders may be removed from the plan until balance is achieved. The proposed information system should work on data from BusinessObjects system.

Planning teams have access to statistics collected during previous years. These statistics show that some periods have higher load, though throughput and mixture of products with quantities are impossible to predict. Tata Steel Europe employees also mentioned that the current manufacturing and planning practices are biased with past knowledge. For example, a mill in Tata Steel Europe Tubes is running for many hours non-stop resulting in buffer overflow and problems with internal logistics. Stopping the mill would result in a few thousand pounds of losses; however, losses from no buffer space or a nearly collapsed internal transportation system are not considered.

Steel manufacturing equipment is an example of massive engineering with long life cycle. It is expensive to install and reallocate. The production systems in Tata Steel Europe Tubes were modified during past decades. The author is sure that each modification makes sense at the time; however, on a larger scale it results a sub-optimal system that can hardly be called lean. With the current marketing trend to customisation, the production planning and operational management teams are facing regular challenges and operate on a fire fighting basis.

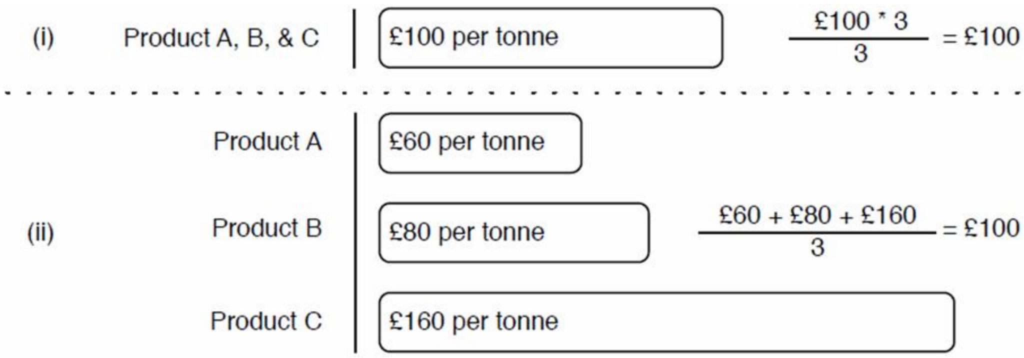


Figure 4.24: Costs for products A, B & C in (i) standard costing system, and (ii) 'reality'.

4.4 Costing in Tata Steel Europe

Tata Steel Europe is managed with standards, which define various aspects of production management, accounting, *etc.* It also uses standard costing approach to calculate production costs, *i.e.* production cost of one production area is measured in a number of GBP per one tonne. For example £100 per tonne on average for three projects, while the real costs are different: £60 for the first, £80 for the second, and £160 per tonne for the third project; see Figure 4.24 – the average cost of all three products is the same, while the 'real' costs are different. In addition, the current marketing trend shows further customisation of products for customers, from a small number of big orders seen a few decades ago to a big number of small orders now; this change makes standard costing approach less feasible to use. As a result, these companies may face difficulties in answering questions such as '*What is the real production cost?*'

Tata Steel Europe produces annual reports defining resource consumption per each production area. Each resource i.e. electricity or water, land or employee, have assigned costs. The combination of resource consumption per area with resource costs allows for estimation of cost per unit of resource for each area. This information is further combined with annual throughput in each area, which allows definition of a cost standard per each tonne of throughput; an example of such costs is given in Table 4.5. This information is enough to perform some accounting and strategic management activities; however, they are not enough for operations management and sales activities.

Finish	CF1	CF2	CF3	CF4	CF5	CF6	CF7	CF8	CF9
P/E Red	8.43	0.00	0.00	0.00	5.96	0.00	0.00	0.00	7.15
P/E Galv	8.43	0.00	0.00	0.00	5.96	0.00	0.00	0.00	0.00
S/S Red	8.43	10.59	0.00	0.00	5.96	0.00	0.00	0.00	7.15
S/S Galv	8.43	10.59	0.00	0.00	5.96	0.00	0.00	0.00	0.00
P/E S/C	8.43	0.00	0.00	0.00	5.96	0.00	0.00	0.00	0.00

Table 4.5: Employee cost GBP per tonne of a product.

During the past decades, Tata Steel Europe was unsystematically implementing a variety of information systems in attempts to differentiate costs. However, due to vast information with ambiguous naming, obsolescence data, changes in production systems and their complexity, Tata Steel Europe employees do not trust these values. For example, Tata Steel Europe Engineering Steel has over one hundred costs, the names of these costs are assembled from those mentioned in Figure 4.5.

This can be solved by redesigning the costing system, for example by implementing activity-based costing for the whole organisation; however, this is a very big project that requires changes in business processes and mentality of employees. A short term solution is proposed in this research project; this solution is described in Chapter 6.

4.5 Discrete event simulation modelling

Tata Steel Research, Development & Technology (RD&T) business unit has been developing DES models for over a decade. The developed models might be re-used for cost estimation; current and future modelling projects may provide additional cost information; and cost estimation may be a major concern in some DES modelling projects. In this case, RD&T must understand what information to collect for developing DES models suitable for cost estimation. In addition to this, development of conceptual (information) models and data collection sometimes take up to fifty per-cent of the lead time of a project, and this is one of the major problems with this methodology.

In addition to time-consuming stages of conceptual modelling and data collection, the author identified the following conditions. Simulation modelling is an iterative process guided by project objectives that can be refined during the project process. A number of

BU	Area	Objective
RD&T	Llanwern finishing end	Remove finishing end congesting & explore lean practices (planning)
RD&T	CES Stocksbridge Finishing Operations	How much material potentially can be produced
RD&T	Shotton supply chain planning (manufacturing)	Design templates investigation manufacturing impact of differing campaign plans

Table 4.6: Shorten list of Tata Steel Europe simulation models.

face-to-face meetings or 'workshops' are typical focal points for information collection. Transformation of notes collected during these meetings into electronic format requires basic skills yet additional time and a disciplined organised approach. Information about some of the elements of a production system is more relevant than information on others. Major information sources usually work on operation and middle level management. These employees are very experienced in their fields but lack DES modelling skills. Their descriptions of production systems tend to be unstructured and anecdotal thus requiring time-consuming reprocessing by a simulation engineer. It is difficult to reuse simulation models that have not been used for a few years. Besides, there are numerous technical issues concerning relevance, quality, and quantity of information, as well as maintaining the storage and access of information.

RD&T BU developed a variety of DES models. Information on these models were collected during this research period and were described with five parameters: a) business unit where a model was built, b) area of steelmaking production, c) business unit or an external company a model was developed for, d) person who was responsible for model development, and e) an objective the model was developed for. Some models are listed in the Table 4.6, while full list of Tata Steel Europe simulation models is possible to find in Appendix A.

Rockwell Arena (http://www.arenasimulation.com/) was used as DES modelling software in the majority of projects; however, Witness (http://www.lanner.com/) and Flexsim (http://www.flexsim.com/) were used as well. At least one third of simulation models in Tata Steel Europe were developed by RD&T BU, which is in total more than 22 models which were developed prior to 2009. Tata Steel RD&T specialists are also involved in some simulation projects outside the company. RD&T experienced simulation engineers are running two-day courses on DES modelling for employees of Corus production business units.

4.6 Summary and challenges

The author believes that academia and science support industry and technology. Cranfield University consulted Tata Steel Europe in a number of research projects. However, intentions of Tata Steel Europe to use DES modelling for solving these problems do not mean that solutions to these problems are related to science, nor proposing the use of DES modelling is correct. Existence of the problems and intentions to use DES must be verified. As described in Sections 4.3 & 4.4, Tata Steel Europe environment is summarised in the following statements.

- Change from a small number of high volume orders few decades ago, to the current big number of low volume orders.
- With the decades of change the current production systems are not designed for the current business requirements.
- Tata Steel Europe is managed with standards, which define various aspects of production.
- A large number of information systems use numerous cost identifies having repetitive naming.

Due to these conditions, Tata Steel Europe has the following challenges:

1. No knowledge on 'real' costs of products and orders.
2. Production planning faces regular challenges that affect manufacturing and dispatching.

The combination of these observations with the findings from the literature review (see Section 2.4) validates the use of discrete event simulation modelling for solving some issues with production planning and costing.

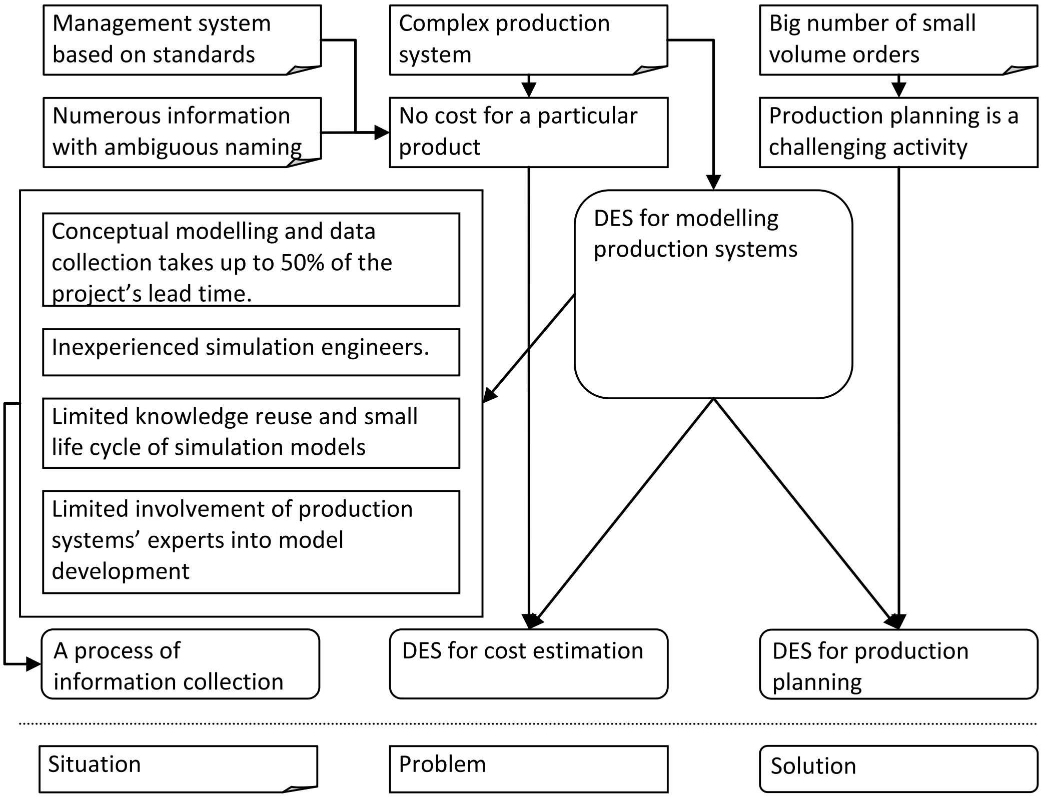


Figure 4.25: Overview of using DES modelling for solving some of problems in Tata Steel Europe.

However, DES modelling has some negative characteristics as it requires skilled personnel for simulation modelling. Development of DES models is a time-consuming process, sometimes data collection and development of information model takes up to fifty per-cent of the lead time of a simulation modelling project. A solution that would guide inexperienced simulation engineers and speed up data collection would be useful for the company. A number of other findings regarding discrete event simulation modelling in Tata Steel Europe are listed in Section 4.5 and Chapter 7. Figure 4.25 contains the overview of using DES modelling for solving some of problems in Tata Steel Europe, while Figure 8.1 visualises areas of impact of this research project to the company.

Five methods for improving production performance were found during the literature review (see Section 2.2.4) including 1) time-sequenced introduction of products, 2) dispatching rules, 3) production parameters, 4) production site's layouts, and 5) a composite solution of two or more above-mentioned approaches. Option No 4 is excluded due to size and cost of reallocating the production site's layout. Option No 3; the production parameters might be very promising for some machines; for example, change of steel processing with cooling may have major impact to properties of the steel; however, it requires thorough study and may not be called a generic solution for the industry. The similar conclusion, but massive changes in manufacturing practices, excludes option No 2 from the list. This leaves option No 1, time-sequenced introduction of products, as a method for improving performance of a production system. This option satisfies the following criteria. It can be used i) to improve production performance, ii) for production planning and scheduling, iii) is generic for manufacturing and iv) does not require major changes in manufacturing practices.

Chapter 5

Optimisation of production plans and schedules

5.1 Introduction

Tata Steel Europe, the second largest European steel manufacturing company has a number of factories mostly located in the UK. Each factory were originally designed to satisfy the demand that is characterised by a small number of high volume orders. Over the past decades, the demand structure has changed to a substantially higher number of low volume orders. In addition to this, a variety of unsystematic modifications changed the production processes. Due to these reasons, planning teams are facing regular challenges. Therefore, a generic yet accurate algorithmic method for the optimisation of production plans and schedules is relevant to this steel manufacturing company.

This chapter covers simultaneous optimisation of production plans and schedules with GA & DES. These concepts have been introduced and rationale provided in Section 2.2, and especially Table 2.2 as well as the related text that describe improving production performance using GA & DES. There are five ways to improve production performance (see Table 2.2 in Section 2.2.4), and one of them – optimisation of time-sequenced introduction of products into a production system is selected for this research.

In these projects, researchers studied optimisation of production schedules for a pre-defined set of products and volumes. The author took this concept further. By working with time-sequenced introduction of products, in addition to optimisation of production schedules, the author aims to optimise the selection of products, and calling it optimisation of production plans and schedules using GA & DES of production systems.

5.2 Optimisation system

The optimisation system used in this research consists of i) a DES model that is used as the fitness function of ii) a GA; data for optimisation studies are taken from iii) a database. This architecture is shown in Figure 5.1. The genetic algorithms' module performs all GA operations except the evaluation of fitness values. At the beginning of an optimisation experiment, it forms production schedules (chromosomes) by extracting data from the database module. The DES model's module evaluates fitness values; each evaluation is a single run of the simulation model. The input data come from both GA module and database. Optimisation results are provided to a planning team at the end of an optimisation run.

The database contains a production plan – a mix of products for production within a limited time period, e.g. two weeks. As different factories process different products, this information differs from case to case; however, each database contains products' unique identifications, associated production volumes, and other characteristics of products used by simulation models. The structure of databases and DES models are kept the same

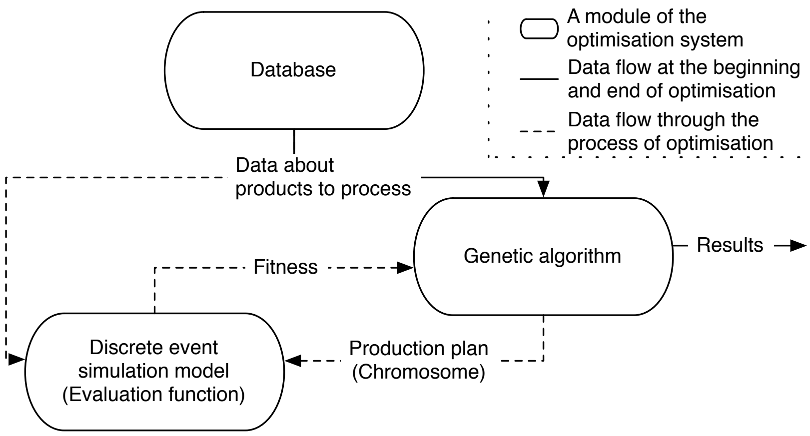


Figure 5.1: Architecture of the optimisation system.

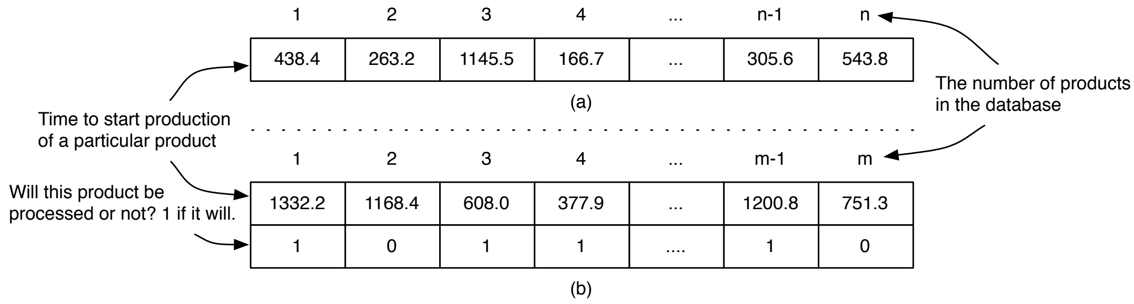


Figure 5.2: Chromosomes for (a) optimisation of production schedule, and (b) optimisation of both and production plan and schedule.

for both 1) optimisation of production schedules and 2) optimisation of production plans and schedules.

The structure of the chromosome is different in these two cases. For the optimisation of production schedules, one-dimensional chromosome contains times when each product is introduced into a modelled production system, this is shown in the part (a) of Figure 5.2. The first value is always reserved for the first product in the database, the second value – for the second product, etc. The time values are limited with start and end times of a DES model's simulation run. The rest of the input information is taken from the database by the simulation model, it is a faster solution regarding the implementation specifics.

In the second case, the chromosome is represented with a two-dimensional array. The first dimension, as described above, is reserved for time, while the second defines whether products should or should not be processed in a single simulation experiment, taking values 1 if this product is included, and 0 if this product is excluded, see the part (b) of Figure 5.2. A combination of products marked with 1, with information such as production period and area represents a production plan, while production schedule is defined by the times these products are introduced into the production system. This chromosome makes possible the optimisation of both production schedules and production plans.

jMetal - Java library of multi-objective evolutionary algorithms is one of the core components of the optimisation system, while the other components are (i) a Rockwell Arena v11 DES model that is used as a fitness function of GA, and (ii) MS Access

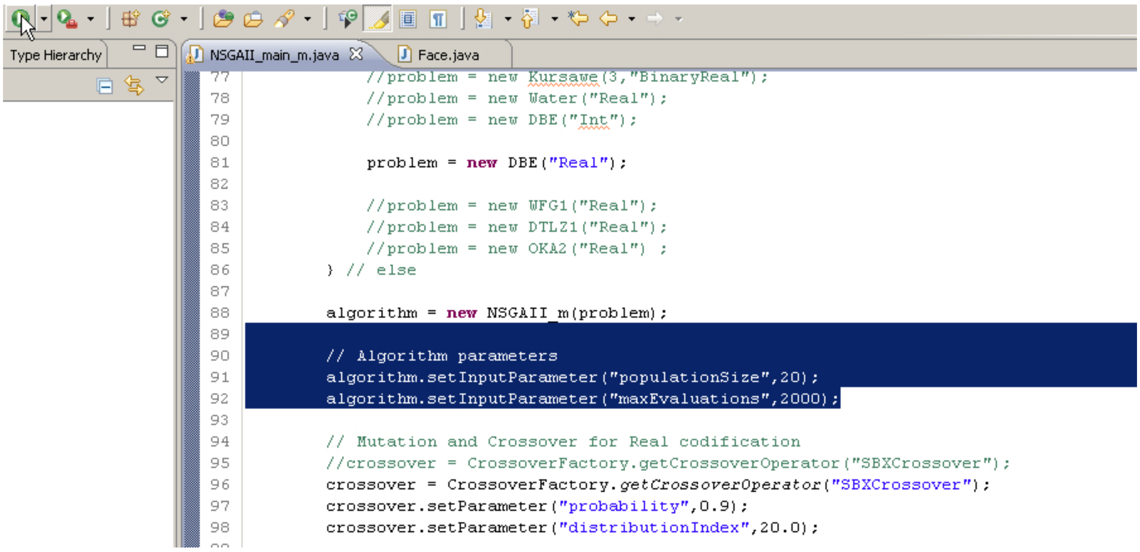


Figure 5.3: Initiation of the optimisation run.

database that contains most of the input data for experiments. A generic flow of the system's operations is shown in Figure 5.6. Optimisation goes through the following steps:

1. jMetal initiates the optimisation run. At this time a genetic algorithm is selected (NSGA-II), parameters are set (population size and number of evaluations, crossover operator and probability and distribution index, mutation operator and probability and distribution index), the size of future chromosomes are defined, fitness function (DES model of production system) and database that stores a pool of products for production are selected and the simulation objectives are defined. This step is shown in Figure 5.3.

2. jMetal pulls data from the database using ODBC that allows MS Access data to be pulled from a Java software (jMetal). ODBC setup is shown in Figure 5.4.

3. jMetal forms a generation. At this time jMetal takes the data and forms a generation according to the settings mentioned in the first point.

4. jMetal initiates a simulation run and pushes one chromosome from the generation to the simulation model. A Java – COM bridge (JACOB) is used for the man-

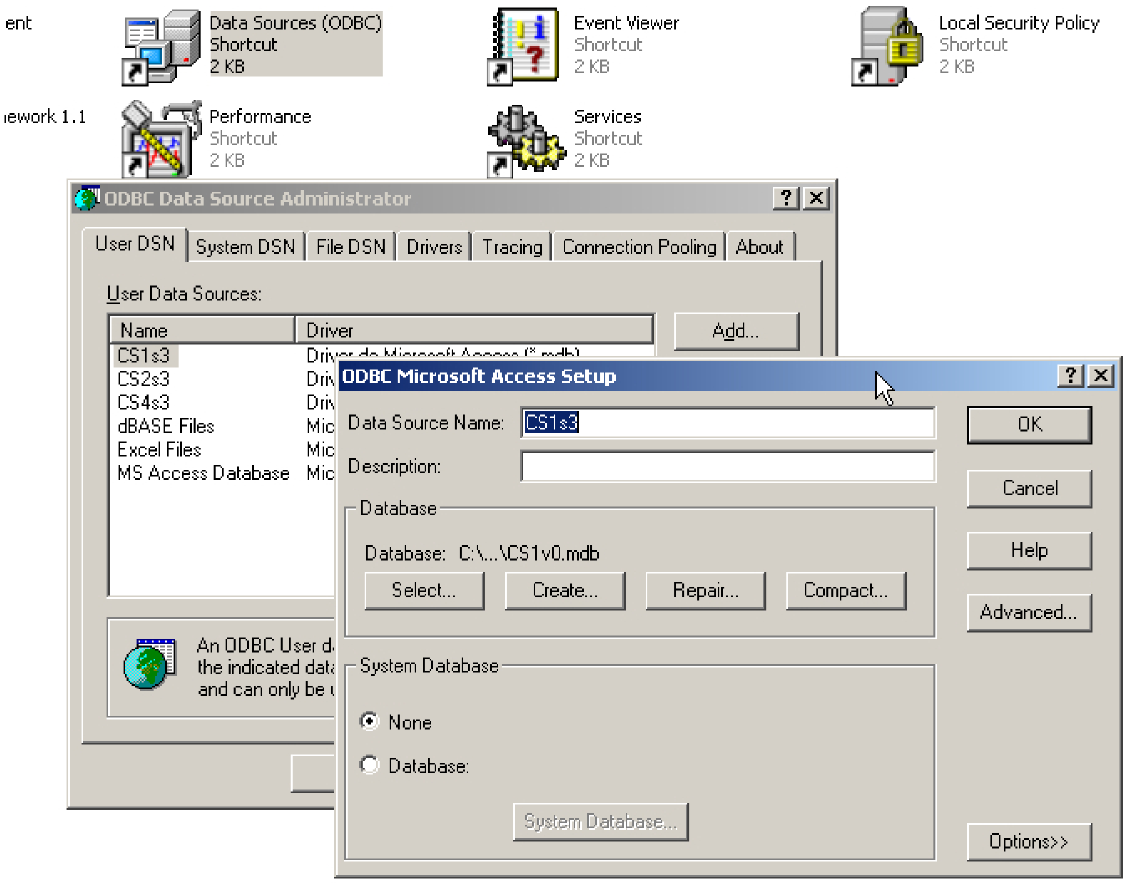


Figure 5.4: ODBC setup.

agement of Arena simulation model from Java software (jMetal). jMetal starts the Arena software, pushes the chromosome, and initiates the simulation run.

5. The Arena simulation model pulls data from the database using the built-in interface in the Arena software. The simulation model identifies the data to pull using identifiers it has received from jMetal. The simulation model pulls all the data required for this simulation run.

6. The Arena simulation model evaluates the fitness values.

7. jMetal optimisation software waits until the simulation run is finished (JACOB is used to track the states of simulation modelling run) and pulls fitness values from the simulation model, and stores these values for further use by the GA operators.

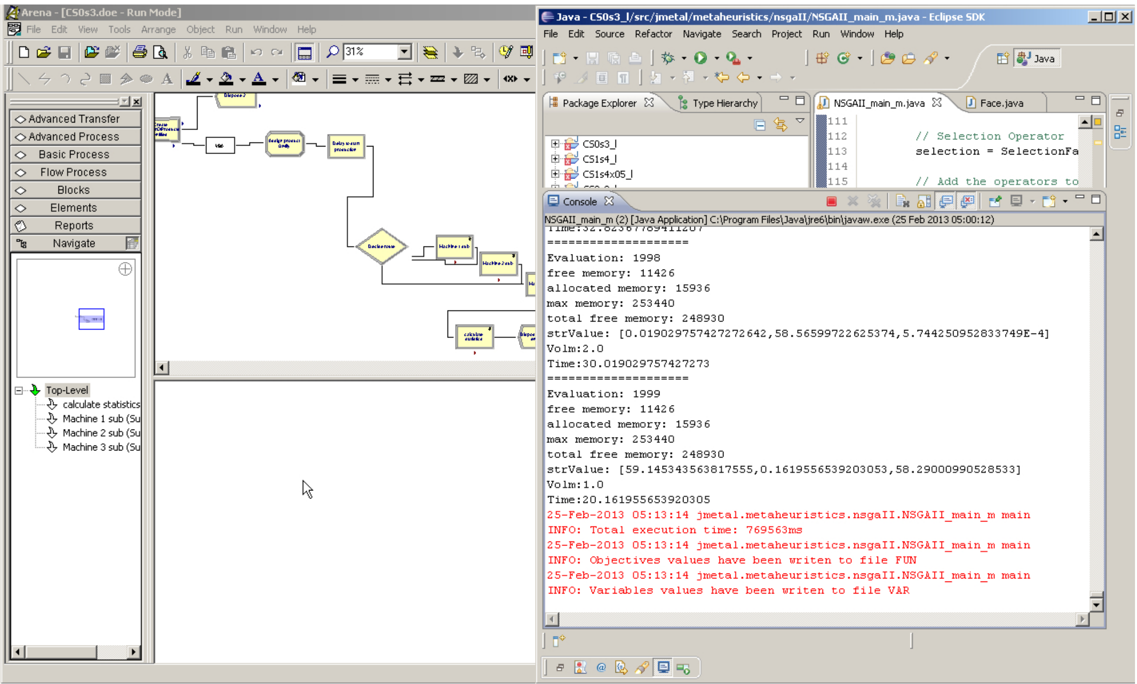


Figure 5.5: End of optimisation run.

If all chromosomes of this generation are processed, jMetal proceeds to the next step, otherwise jMetal starts with the next chromosome from the fourth point.

8. jMetal processes operators of GAs and if this is the final generation, it stops the optimisation, otherwise it generates a new generation and the optimisation starts from the fourth point. End of the optimisation run is shown in Figure 5.5.

A sample of the database is shown in Figure 5.7. One data row describes one product, the first row is related to the first element in the chromosome, the second – to second, etc.

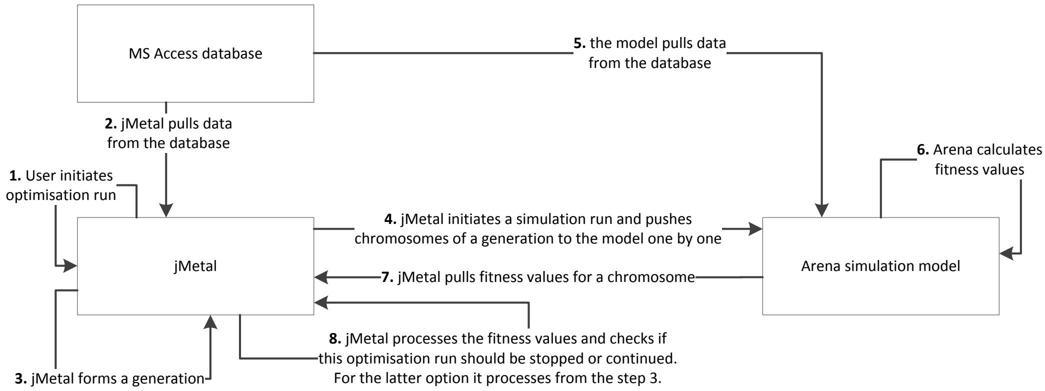


Figure 5.6: Data flow during optimisation.

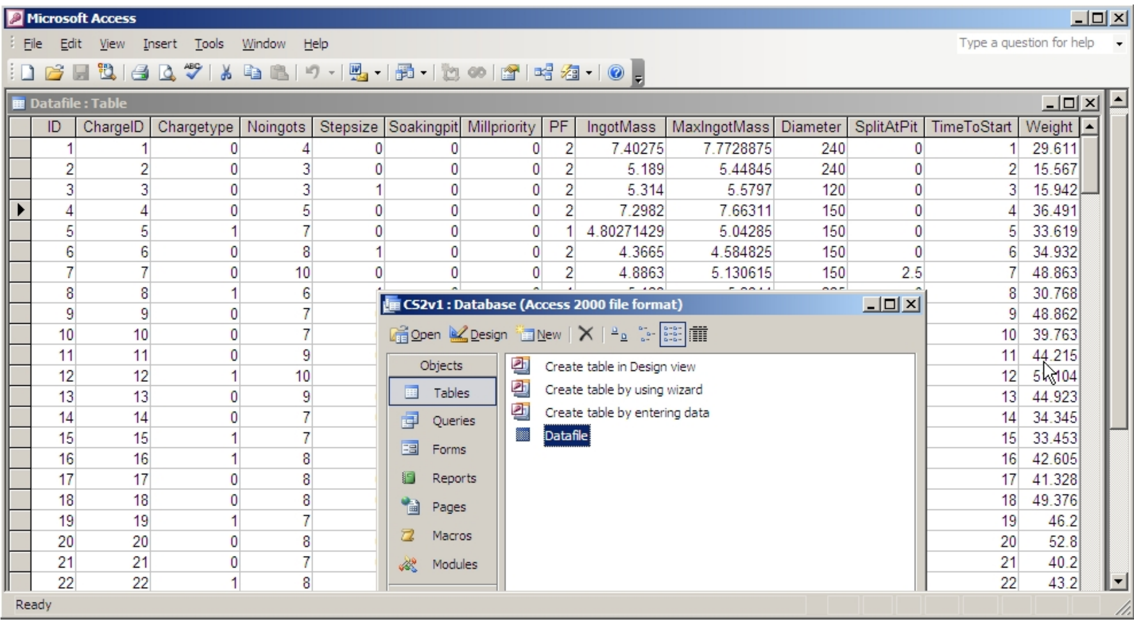


Figure 5.7: Example of database that contains data for experiments.

5.3 Validation

This section systematically validated the studied concept – simultaneous optimisation of production plans and schedules using DES models as fitness functions of a genetic algorithm. The author developed the matrix for systematic validation of a research concept. This is a three by three matrix, or a bi-dimensional matrix with three levels on each dimension. The first dimension covers a system view to the concept; and it

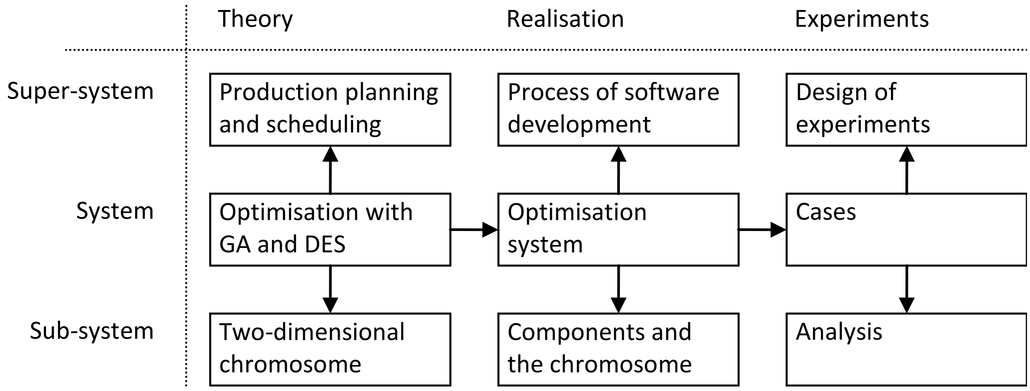


Figure 5.8: Elements of the systematic validation of the optimisation's part of research.

consists of a super-system, system, and sub-system levels of the concept. The second dimension covers theoretical, realisation, and experimentation part of the research. The systematic view consists of nine elements, and if all of them are valid, then the research is valid as well.

The core research concept is the simultaneous optimisation of production plans and schedules using a DES model as the fitness functions of a genetic algorithm. This core concept fills the system level of a theoretical part of the matrix. This optimisation system is used for production planning and scheduling (PPS); therefore PPS fills the super-system level of the theoretical part of the matrix. The optimisation system consists of a genetic algorithm and a discrete event simulation model. Each of these components has its own specifics; therefore, these components fill the sub-system level of the theoretical part of the matrix. The matrix is shown in Figure 5.8.

The validation of production planning and scheduling is different to validation of the components of the optimisation system; therefore, different criteria and methods are used. The summary of the validated methods and related criteria and methods is provided in Table 5.1. This information is described in the rest of this section in detail.

The author chose a pragmatic approach in this research, as Robson [152] defined 'use whatever philosophical or methodological approach works best for a particular research problem at issue.' Therefore, unstructured interviews and participant observations were

Part	Level	Elements	Criteria	Methods of validation
Theory	Super-system	Production planning and scheduling	Optimisation system can be used within constraints	Literature review, logical reasoning.
	System	Optimisation with GA & DES	Optimisation system provide the required functionality	Literature review
	Sub-system	Two-dimensional chromosome	This chromosome supports both production planning and scheduling.	Logical reasoning
Realisation	Super-system	Process of software development	The used process has similarities to an existing process of software development.	Logical reasoning
	System	Optimisation system	Optimisation system works.	Testing
	Sub-system	Two-dimensional chromosome	The components provide the required functionality.	Testing
Experiment	Super-system	Design of experiments	A set of experiments may be used to test the research idea.	Logical reasoning
	System	Cases	Cases are industrial and relevant.	Observations, interviews, and logical reasoning
	Sub-system	Analysis of the hypothesis	Production planning and scheduling in comparison to production scheduling	Logical reasoning

Table 5.1: Summary of the validation process.

selected because the research objects are complex and limited in numbers. Various aspects of a big company and DES modelling projects make less feasible the use of structured methods of information collection. Similar argumentation is applied at the selection of case studies instead of thorough experiments.

The company funds this research because of challenges it faces with production planning and scheduling. The existence and specifics of these challenges were validated with a number of unstructured interviews and informal observations within the company. Discrete event simulation was compared with other methods of simulation modelling and approved as a method for modelling complex production processes within the company, while genetic algorithms were selected as a meta-heuristic optimisation method used in all types of scheduling problems.

Time-sequenced introduction of products into production system was selected as the most appropriate method to optimise production schedules within this research. The author developed the hypothesis, that is, it possible to optimise both production plans and schedules simultaneously, and that this may outperform the 'standard' optimisation of production schedules. In order to test this hypothesis, the author developed a composite software and utilised three industrial cases.

5.3.1 Theory

Super-system – theoretical level. Production planning and scheduling is reviewed in Section 2.2.1; using terminology from Figure 2.1, this research covers short-term planning and scheduling for production stage. The developed optimisation system provides sets of nearly-optimal production plans and schedules for further selection by production planners, and works with time periods that are up to few weeks long (see Table 5.5). Therefore, it is valid to use this optimisation system for production planning and scheduling, which means that the researched concept passes theoretical validation on a super-system level.

System – theoretical level. Maravelias and Sung [14] state that 'short-term planning is carried out on a daily or weekly basis to determine the assignment of tasks to units and the sequencing of tasks in each unit. At the production level, short-term planning is referred to as scheduling.' Production plans and schedules are closely interrelated concepts [15]: the plan is a definition of product mixes and quantities a company is expecting to produce, while the schedule represents a time-sequenced introduction of products into a production system that efficiently supports a plan. The optimisation system defines both product mixes and quantities of production, and defines time-sequenced introduction of products (see Figure 5.2). Therefore, this optimisation system provides the functionality and passes theoretical validation on a system level.

Sub-system – theoretical level. The main difference between a variety of GA & DES based optimisation systems (see Section 2.2.4) and the one described in this research is a two-dimensional chromosome. As described in Figure 5.2 and the related text, the following information is encoded in this chromosome: a) a product, b) time a product is sent for production, c) is a product going to get produced. According to definitions from the previous paragraph, this chromosome contains both a production plan and production schedule; and if such a chromosome is used in an optimisation

Iteration	Work on
First	Data transfer between jMetal and Arena
Second	Simple optimization experiment using jMetal and Arena
Third	Optimisation of production schedules
Fourth	Optimisation of production plans and schedules

Table 5.2: Four iterations of developing the optimisation system

system, then this system optimises both production plans and production schedules. Therefore, it passes theoretical validation on a sub-system level.

5.3.2 Realisation

Super-system – realisation level. The optimisation system is a piece of software engineering, and it was developed using an iterative process of software development. This process was selected due to a number of software components that were new to the author and novelty of the topic (considering a programming aspect in both of the cases). As this process utilises learning-by-doing concept, this method has advantages to other processes of software development (i.e. Waterfall model). As the selection of the iterative and incremental development process was rational, and the process was used in the development of the optimisation system (see Table 5.2 and the related text); then super-system level at realisation part of the research is valid.

System – realisation level. jMetal implementation of NSGA-II algorithm was selected, as this library had been designed for fast and easy changes of optimisation experiments [162], while NSGA-II is widely used for multi-objective optimisation. Simulation models were developed in Rockwell Arena v11; the major DES modelling software of the host company. An iterative approach was selected for software development, which was further used for the comparison; four iterations were performed in total. The first iteration included building a simple data communication between jMetal and Arena. The second iteration represented a run of a simple optimisation experiment using jMetal and Arena. The next step was optimisation of production schedules. Optimisation of production plans and schedules was performed in the fourth iteration of software development. The overview of iteration is provided in Table 5.2.

The optimisation system is tested on a simple example. If the results of optimisation correspond to theoretical optimum, then the optimisation system would be proved valid. The optimisation system consists of a GA and simulation modules, which is used as a fitness function of this GA. Therefore, according to Figure 5.1, the following elements must be tested: GA, simulation model, data transfer.

jMetal Java library of multi-objective evolutionary algorithms was selected for use in this optimisation system, and NSGA-II was selected for the implementation. This library was tested on Kursawe's problem, the optimisation results were plotted and further compared with plots from Kursawe's paper [163]; these plots are shown in Figure 5.9 (jMetal plots on top, and the bottom plots came from the paper). As the problem's implementation in jMetal corresponds to the equations from Kursawe's paper, and the plots look similar, then jMetal is a valid component of the optimisation system.

A simple simulation model is used for testing the optimisation system, this simulation model is described in Figure 2.6 and the related text. The simulation model is shown in Figure 5.10. This model was tested on the best and worst case scenarios; the results are the same to the results in Section 2.4.3. Therefore, this simulation model, while being used with a GA, could be used to prove that the optimisation system (GA & DES) provides optimal results.

This simulation model was connected to NSGA-II, and the optimisation system was tested on one experiment. The simulation model was setup to run for a maximum of 1 hour (60 minutes), therefore each of the three products was sent for production within 60 minutes time. Two objectives were used: time of the last processed product (to minimise), and overall throughput (to maximise). The optimal values are 30 minutes and 3 products. The following parameters of NSGA-II were used:

- Population size: 20; number of evaluations: 2000 (100 generations).
- Crossover: SBX crossover; probability 0.9, distribution index 20.
- Mutation: Polynomial mutation, probability 0.01, distribution index 20.
- Selection: Binary Tournament (2nd jMetal's version).

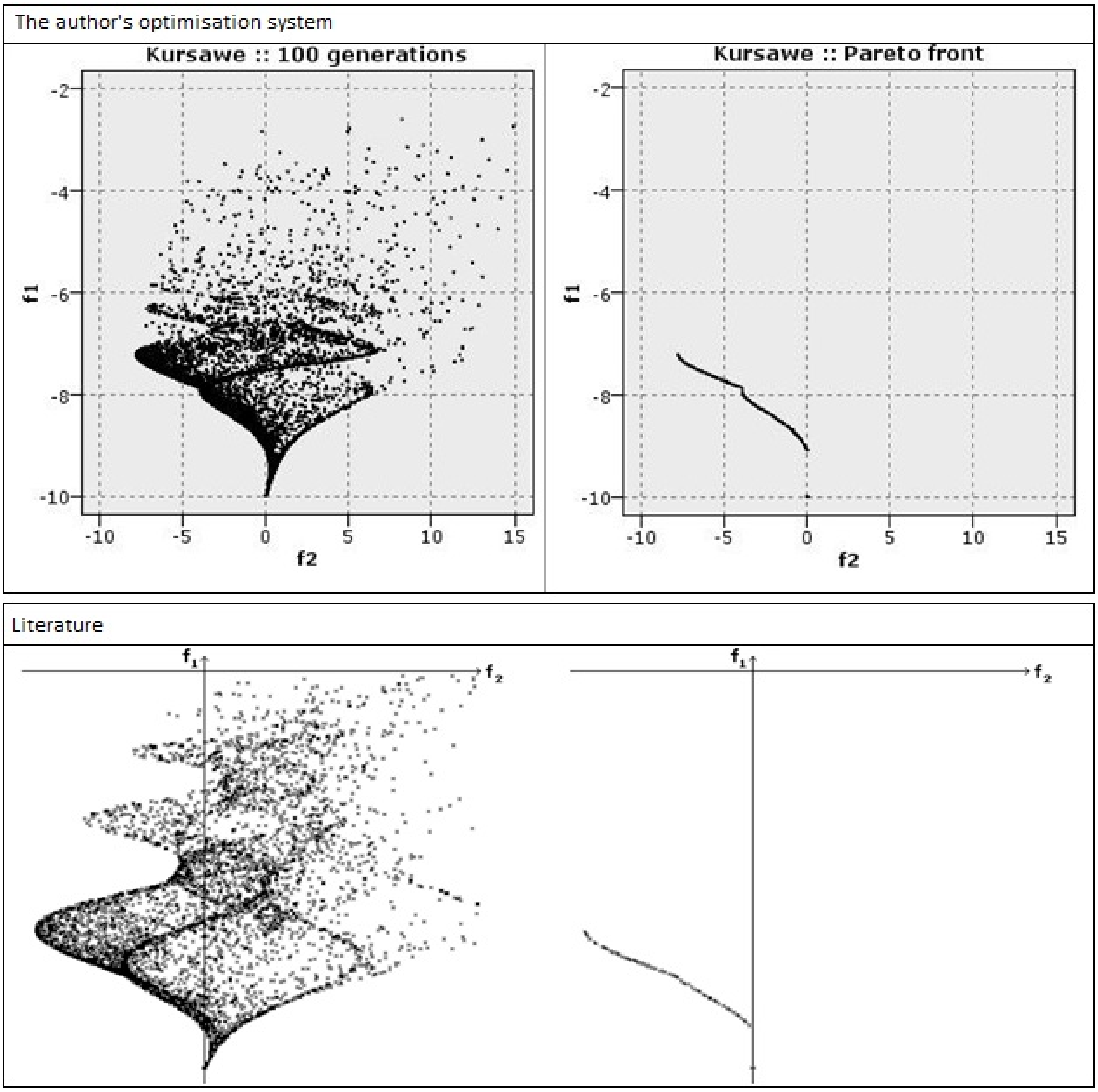


Figure 5.9: Comparing Kursawe's problem: the top two plots are jMetal's NSGA-II, and the bottom figures come from Kursawe's paper [163].

The optimisation results in Figure 5.11 prove that this realisation of the optimisation system (GA & DES) can be used to optimise production schedules; therefore, this validates the system level of the realisation part.

Sub-system – realisation level. This simple theoretical example illustrates optimisation of a production schedule (iteration 3 by terminology from Table 5.2), which partially validates optimisation of production plans and schedules (iteration 4). These versions of optimisation system have two major differences in programming code; these differences are related to Figure 5.2 and the related text. The first difference is in

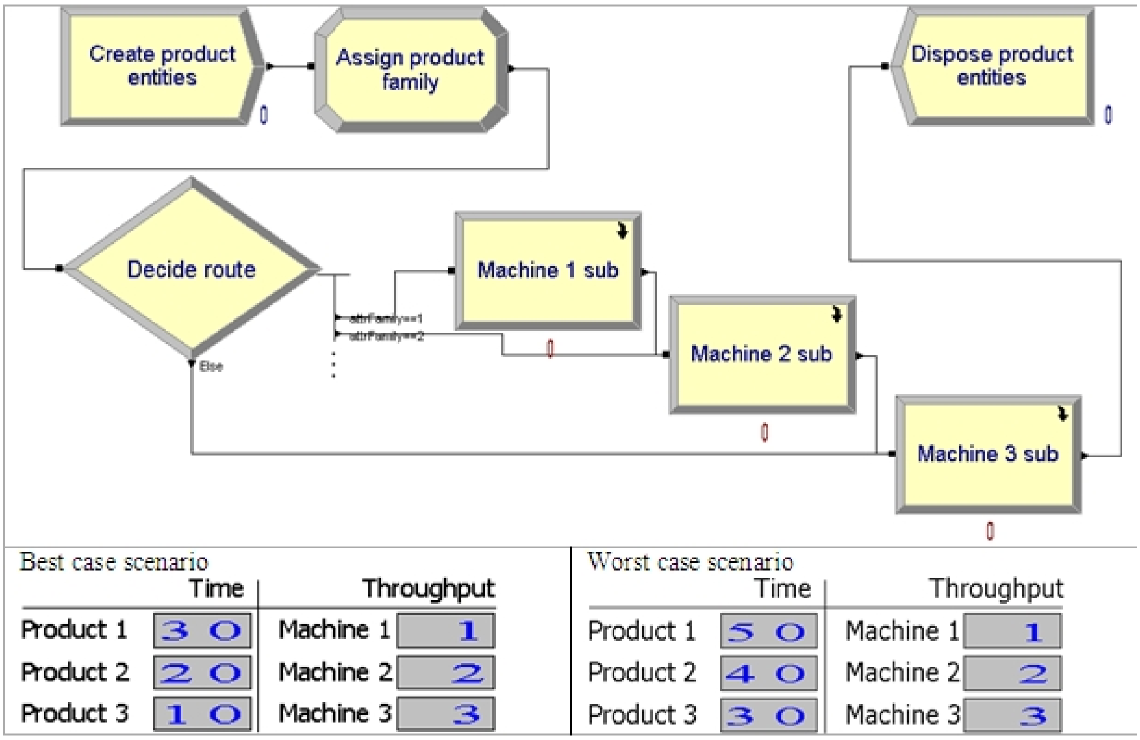


Figure 5.10: Simulation model used to test the optimisation system.

data structures: either an array of time values was sent to a simulation model during Iteration 3, or an array of time values and an array of binary values (would or would not a product be processed) were sent to a simulation model during Iteration 4. The second difference is in the utilised crossover operation; again it is related to the second dimension. These differences are illustrated in Table 5.3 that contains an example of programming code. These changes are simple, the mistakes are easy to track (by printing these arrays to a console and analysing this information, and the author found no mistakes – all the data transfers were correct); therefore, this validates the sub-system level of the realisation part of research.

Description	Code
Iteration 3, data structures	`public void setEvaluationData(Double[] dblDatabaseDataArray,` `Real[] timeArray) {`

Iteration 3, Crossover	`offSpring[0].getDecisionVariables().variables_[i].setValue(c2);`
	`offSpring[1].getDecisionVariables().variables_[i].setValue(c1);`
	`} else {`

Iteration 4, data structures	`public void setEvaluationData(Double[][] dblDatabaseDataArray,` `Real[] idArray, Real[] timeArray) {`

Iteration 4, Crossover	`if (PseudoRandom.randDouble()<=0.5) {`
	`offSpring[0].getDecisionVariables().variables_2[1][i].setValue(c2);`
	`offSpring[1].getDecisionVariables().variables_2[1][i].setValue(c1);`
	`offSpring[0].getDecisionVariables().variables_2[0][i].setValue(d2);`
	`offSpring[1].getDecisionVariables().variables_2[0][i].setValue(d1);`
	`} else {`

Table 5.3: The differences in code between iteration 3 and iteration 4.

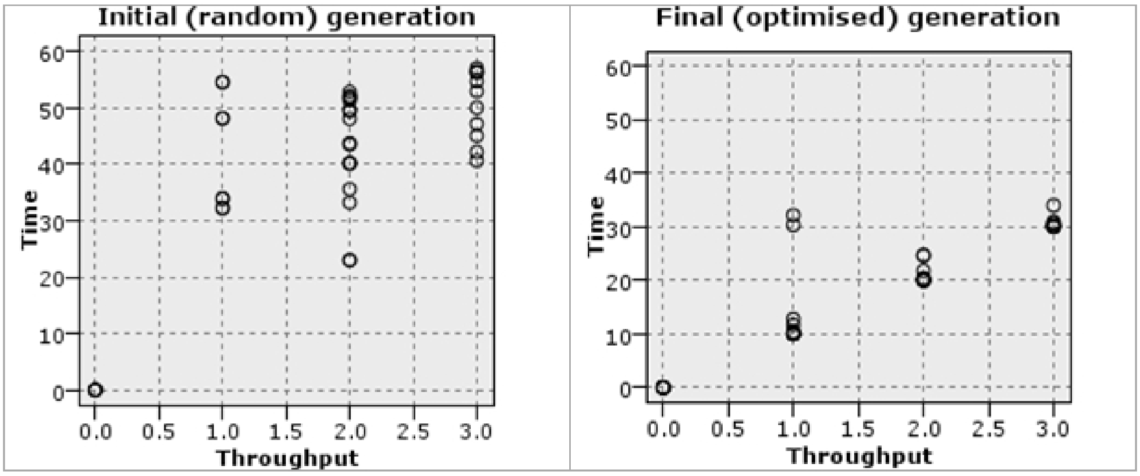


Figure 5.11: Testing the optimisation system: initial and final generations.

5.3.3 Experiments

Super-system – experimentation level. The optimisation system consists of the genetic algorithm and discrete event simulation model of a production system. The genetic algorithm and its parameters are the same during all experiments; the major difference between experiments is related to discrete event simulation models. Each of these models represents an industrial production system: complex, stochastic, and dynamic process – an industrial case. Three cases of multiple complexity were studied in order to validate this part of the research. As this research is also related to experiments with a genetic algorithm, and this incorporates random initial generation, then from five to twenty experiments with each case there is a common practice; and as GA & DES requires computational powers, five experiments with different random seeds were selected. Each genetic algorithm has a set of parameters, and the 'common' parameters for NSGA-II were selected: SBX crossover operator with crossover probability of 0.9 and distribution index of 20, polynomial mutation operator with mutation probability of 0.01 and distribution index of 20, binary tournament No 2 as a selection operator. The population size was 100 individuals and 10'000 evaluations within an optimisation run. This design of experiments validates super-system level of the experimental part of the research.

System – experimentation level. Three industrial cases are used in this research. 'Industrial' means that a case is either i) developed by an industrial simulation engineer, is verified and validated by a manufacturing manager, and is used for industrial purposes (cases No 2 and 3) or ii) is developed by the author, validated by industrial simulation engineer and manufacturing manager, and is used for their purposes (case No 1). This proves that each simulation model provides accurate results.

Each of the simulation models uses time-sequenced introduction of products as the input and provides a number of key performance indicators as the output; therefore, it can be used for production planning and scheduling. All simulation models are different to each other in terms of products, production systems, size of production systems, and depth of simulation modelling; therefore, this set of simulation models provides diversity for the experiments. This validates the system level of the experimentation part of the research.

NSGA-II has a number of parameters that affects its performance [9]. Crossover, mutation and selection operators perform the basic functions of GA. 100 as the size of a population with the total number of evaluations of 10'000 is the de-facto standard and it is a good place to start; however, these parameters are problem specific and may be adjusted on a case basis. It is recommended to setup the probability of mutation as 1 divided by the number of individuals in population (0.01 in the de-facto case); while probability of crossover is usually close to 1. Distribution indexes for mutation and crossover is the last set of parameters; these parameters define how close an offspring would be to parents.

The following parameters of NSGA-II were used: SBX crossover operator with crossover probability of 0.9 and distribution index of 20, polynomial mutation operator with mutation probability of 0.01 and distribution index of 20, binary tournament No 2 as a selection operator. The population size was 100 individuals and 10'000 evaluations within an optimisation run. The experiments were grouped into sets, within a set each case was run five times with different random seeds. One set of experiments was performed within Iteration No 3, two sets experiments were performed within Iteration No 4. The difference between two sets of Iteration No 4 experiments is related to the

Case study	Stage 3	Stage 4	
		(a)	(b)
Case study 1	15	15 – 22	15 – 30
Case study 2	220	220 – 270	220 – 440
Case study 3	28	28 – 42	28 – 56

Table 5.4: No of products in each case study.

Code	Description	Objectives	Period
CS1	A critical production area in Tata Steel Europe Tubes.	Maximise throughput, and minimise overall production time	1 week
CS2	A heating end area in Tata Steel Europe Engineering Steels.	Maximise throughput, and minimise weighted measure of time delays on a specific stage of production	4 weeks
CS3	Shotton flow model.	Maximise throughput, and minimise stock	4 weeks

Table 5.5: A generic description of case studies used in this research.

number of products in the databases, (a) 1.5 times and (b) 2 times more than as used at the Iteration No 3. In addition, a convergence check was performed for each case and iteration with 50'000 evaluations (higher numbers of evaluations crushed Rockwell Arena simulation models). On the Iteration No 4, SBX crossover operator was modified to deal with two-dimensional chromosome. Typical parameters of computers used in experiments were P4 2 GHz, 1GB of RAM, Windows XP. The impact of the length of a chromosome to results was tested in these subsets of experiments. These numbers are summarised in Table 5.4.

5.3.3.1 Case studies

In order to perform testing and validation of the optimisation of production plans and schedules via two-dimensional chromosomes, three case studies were used in this research. Each case is based on the DES model of a steel manufacturing production system. It is difficult to compare different simulation models as no comprehensive classification of DES models was found in literature. The objective functions are a combination of outputs from simulation model. These outputs were selected on the basis of simulation model specifics. A short description of these models is provided in Table 5.5, while more information is provided in the next paragraphs.

A simulation model may be treated as a 'black box', which provides a set of outputs from a set of inputs. In this research, 'black boxes' are discrete event simulation models of steel manufacturing production systems. Typical elements of production systems [148] are processes, products, stores, transporters, resources, and relationships.

Simulation models can be characterised by the size and level of depth the production systems had been modelled. The size of a production system may be 'small' in a case of one or few machines, 'medium' in the case of a group of machines and 'large' in the case of a factory having few groups of machines. The level of depth may be 'generic' in the case of high-level representation of information elements, 'detailed' in the case of low-level of details of these elements, and 'medium', which is in between the generic and detailed levels.

Case study 1. A simulation model represents one production area in Tata Steel Europe Tubes, see Section 4.2.3 for more details. This simulation model was developed by the author with further validation by production experts from Tata Steel Europe Tubes. This production area consists of eleven machines, excluding buffers, loading tables, and cranes. These machines form a semi-sequential production process with two product entry and one exit points; parallel processing is not possible. External logistics is modelled with an entity generator, while internal logistics is represented with conveyors and a crane. Considering the number of basic information elements in this production system (processes, products, stores, transporters, and resources) and the implementation of relationships between these elements, this model may be stated as a medium depth simulation model of a medium size production area.

Table 5.6 shows three samples for CS1i3, CS1i4*1.5, and CS1i4*2. Each of these three samples belongs to Pareto front of 100th generation. The sample shows fitness values and related chromosomes.

Case study 2. A simulation model represents one production area in Tata Steel Europe Engineering Steels, see Section 4.2.5 for more details. This model was developed by simulation modelling experts from Tata Steel Europe Research & Development and validated by production experts from Tata Steel Europe Engineering Steels; R&D personnel later explained this simulation model to the author. This area consists of

Iteration	Throughput	Time	Chromosome
i3	45.4	101.3	6.6 51.9 37.1 41.3 21 12.8 44.7 1.4 61.2 48.1 64.6 27.5 40.8 15.1 32.4
i3	39.1	40.5	12.6 49.2 29.8 3.3 73.8 26.4 56.8 18.9 72.2 54.8 66.7 11 36.9 74.4 11.4
i3	21.7	15.2	70.8 73.7 20.1 34 71.8 70.3 73.5 50.3 72.3 26.8 71 74.1 19.7 39.5 23.8
i4*1.5	65.3	154.7	0 1 1 1 1 1 1 1 1 1 0 1 0 1 1 1 1 1 1 1 1 1 22.8 44.1 60.4 20 30.3 55.9 22.3 44.6 61.2 15.5 20.8 64.9 19.8 16 52.8 27.1 70.9 65.1 13.3 4.1 38.6 57.4
i4*1.5	39.1	25.9	0 1 1 0 0 1 1 1 0 0 0 0 0 0 0 0 1 0 1 1 1 38.3 19 54.1 19.7 68.9 8.1 27.4 3.3 0.2 55.6 54.2 60.6 0.2 63.5 37.3 11.4 39.6 3 44.9 73.9 61.7 15.8
i4*1.5	2.3	0.2	0 0 0 0 0 0 0 0 0 0 1 0 1 0 0 0 0 0 0 0 0 72.5 24.3 49.2 34.9 47.9 28.3 6.4 9.9 17.4 53.5 69.3 47.3 7.5 55.2 13.7 62.1 53.7 38.2 73.2 45.3 30.2 54.4
i4*2	60.4	117.1	1 1 1 0 0 0 0 1 1 1 0 1 0 0 0 1 0 1 1 0 0 0 0 0 0 0 0 0 0 1 1 1 0 0 0 0 0 1 0 0 0 0 0 0 68.3 4.8 11.3 34.7 7.1 72.5 44.1 54.2 10.6 13.9 49.7 74.4 54.4 45.6 46.4 17.9 20.2 61.8 18.8 74.3 44.5 7.5 37.7 27.2 72.2 4.2 13.3 62.8 4.1 19.4 32.2 31.2 34.7 74.7 29.5 23.3 72.9 63.1 50.4 66.7 42 27 60.6 64 23.2
i4*2	40.5	30.8	0 0 1 0 0 0 0 0 0 0 0 0 1 0 0 0 1 0 1 0 0 1 0 0 0 0 0 0 1 0 0 1 1 0 0 1 0 0 0 0 0 0 0 0 0 29 74 58.9 72.3 44.4 54.6 47.7 69.6 6.4 0.5 44.8 45.2 4.8 43.3 18.8 59.7 25.7 39 42.9 13.6 58.2 14.2 3.2 63.5 6.4 43.2 11.5 42.2 63.1 39.6 29.4 34.7 9.4 62.6 69.8 45.5 47.5 12 45.9 54.3 30.3 39.1 73.1 67.6 29.3
i4*2	2.7	0.2	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 1 0 0 64.5 55.8 72.2 59.7 8.5 4.4 16.9 0.6 32.1 6.7 38.4 4.6 49.7 8 14.1 13.8 30.9 22.4 2.6 47.8 5.1 32.7 41.1 33.2 14.5 8.5 29.6 44.9 40.7 72.6 22.5 24.7 31.8 19.1 18.8 73.5 12.9 71.2 34.2 6.1 64.1 7.6 35.9 11.1 30.3

Table 5.6: Samples from Pareto front, case study 1.

two pre-heating furnaces, a number of soaking pits and one mill excluding two cranes and charge units. These machines form a semi-sequential production process with two product entry and exit points. The external logistics is modelled with an entity generator while internal logistics is represented with cranes. Considering the number of basic information elements in this production system and the implementation of relationships between these elements, this model may be stated as a detailed simulation model of a small production area.

Table 5.7, 5.8, and 5.9 shows three samples for CS2i3, CS2i4*1.5, and CS2i4*2. Each of these three samples belongs to Pareto front of 100th generation. The sample shows fitness values and related chromosomes.

Case study 3. A simulation model represents a production system in Tata Steel Europe Colors, see Section 4.2.6 for more details. This model was developed by simulation modelling experts from Tata Steel Europe and validated by production experts from Tata Steel Europe Colors; R&D personnel later explained this simulation model to the author. This area consists of a number of production bays, buffers, external and internal transportation systems. Considering the number of basic information elements in this

Throughput	Time	Chromosome
8582.3	7200	799.8 1285.1 308.7 524.9 671.5 963.3 160.2 1232.7 1020 1041.5 560.8 617.3 136.4 1021.4 715.1 1044.1 1147.8 1174.9 1162.1 1222 790.6 1137.6 573.1 708 989 239.4 965.2 924.1 396.5 597.6 335.8 198.7 1164.9 623.3 1234.9 497.5 950.3 336.2 1143.3 974.8 103 881.2 337 1142.4 1257.3 513.4 730.1 697.4 1245 885.5 176 725.6 855.7 851.6 486.1 178.4 671.5 994.8 586.9 115.3 531.2 1035.9 711.6 353 699.5 579.1 573.3 851.8 1270 957.5 674.5 877.6 1132.3 671.6 563.1 325.8 125.9 723.6 405 738.4 1019.5 1124 56.9 793.6 610.1 13.6 134 623.2 674.2 24.7 480.9 789.7 563.8 1032.2 1305 1177.6 536 675.2 512.2 1180.1 709.3 316.9 1227.4 814.6 806.8 484.9 686.1 501.7 96.9 790.3 958 1132.3 707.5 506.4 1058.9 1129 1060.2 504.6 1175.1 480.5 438.2 266.2 1182.7 958 685.6 380.5 1118.6 792.9 199.4 1257.9 467.4 26.3 122.2 515.1 1266.4 544.9 1054.3 307 451 692.9 365.8 710 1094.5 1123.2 1164.3 38.5 983.9 1010.9 903 848.3 898.4 600.4 1076 768.7 1178.5 899.8 728.5 948.8 1164.4 1117.7 1243.5 675.3 1244.5 901.1 579.7 773.1 1027.1 711.1 582.9 521.9 986.1 1156.1 1222.9 1235.4 832.8 1257.2 665.5 400.4 1185.3 1166.5 1234 1225.8 801.3 1117.1 916.4 1149.4 584.5 848.8 1209 1206.2 594.2 279.1 477.4 794.7 770.7 1248.5 847.4 906.4 1085.7 1035.2 1264 827.6 1213.6 1091.2 1119.5 956.6 671.3 84.2 1145.5 986.2 1058 70.5 1238.4 436.5 856 77.6 678.5 129.1 840.1 1014.1
8451.8	7020	722.8 903.1 308.7 521.2 672.4 911.8 160.2 1253.6 861.9 1063.1 536.7 689.8 343.4 990.7 671.2 1041.3 510.8 1128.3 845.3 555.4 720.2 1146.7 573.1 722 993.8 240 965.2 915.9 401.3 1050.2 335.3 197.5 1164.7 1243 1241.1 496.8 930 336.6 1142 823.4 1254.6 726.9 336.7 1085.8 1110 513.5 732 701.1 1165.5 885.7 174 733.6 864.4 851.2 1096 173.7 671.6 994.8 586.4 115.4 536.1 1039.9 711.8 352.3 699.5 583.7 573.8 851.1 1240.1 1059.3 678.7 866.7 1152.3 726.9 702.7 324.8 576.8 734.1 484.1 1261.7 1026.7 1125.8 55.5 793.1 641.7 27.4 172 1056.7 571.3 595.8 706.7 284.1 489.3 1064.6 1307.5 1133.1 538.9 692.8 497.3 1190.6 721.8 315.5 1232.1 814.2 806.9 484.9 723 499.9 109.3 789.2 964.2 1129.7 678.3 507 1058.9 1127.3 1060.7 505.2 1207.7 491.2 1172.2 802.5 1184.2 1142.4 688 551.6 1132.5 709.9 909.8 1257.7 467.5 22.5 214 515.3 1320.8 575.9 1055 356.3 895.7 450.8 353.6 709.4 1160.9 850.7 1232.5 38.5 978.4 1045.4 901.8 848 897.9 523.9 1077 770.3 1183.1 880.9 878.8 1004.5 1161.9 1162.9 1252.7 673.4 474.2 901.4 590.4 776 1026.9 697.3 573.6 521.7 982.5 1154.5 1219.2 1030 815.6 1242.8 659.3 401 1190.2 1171 1233.8 1150.5 801.3 1113.9 904.2 1249.4 584.3 817 938.9 906.9 594.2 606.2 467 809.7 696.2 1245.9 1156.9 906.4 968.5 1033 1264.1 698.3 1226.9 1097.8 1118.9 991.3 671.3 68 1127.4 990.3 1199.4 70.9 1238.2 423.5 853.6 52.8 963.7 140.9 670 1009.9
8213.3	7830	197.5 735.2 586.1 962.1 187.6 1199.6 1249.6 282.4 271.3 614 268.1 527.1 1208.8 869.7 1205.2 1130.1 472.9 37.2 495.6 1163.4 717 929.9 1062.5 333.1 4.4 738.4 954.7 495 881.6 1257.1 63.3 322.6 1181.9 1324.4 1114.8 825.4 697 1124.5 876.9 571.4 1315.2 633.6 1317.1 1212.7 720.1 1042.4 338.4 819.7 67.7 1015.3 1218 553.2 808.7 795.4 471.9 1187.1 1048.5 965.2 514.8 705.8 552.2 743.5 578.1 1199.5 966.9 547 637.7 1100.5 1206.8 1276.9 981.5 396.3 1119.9 176.8 1113.7 866.2 859.6 712.4 599.3 1308.2 547.8 266.8 630.9 954.9 1244.7 478.9 283.4 569 1116.8 694.5 169.9 549.2 1044.3 1176.1 191 249.4 909.5 276.1 254 165.4 392.4 338.1 1013.1 1109.2 781.6 207.9 106.7 916.1 1211.7 181.4 952.5 607.6 1036.7 1088.2 252 560.5 801.9 972.3 1189.1 569.6 951 814.8 399.2 676.6 1065.6 1229.3 571.9 418.5 239.7 490.8 1280.8 580.4 349.4 1125 1260.1 1048.8 991.5 928.5 636.3 538.9 1193.2 209.9 1120.3 1091.9 923.2 321.3 1303.8 264.3 794.2 1104.9 246.9 1246.1 380.2 961.2 552.1 971.5 787.4 822 285.2 971.9 734.2 967 862.8 328.2 947.6 635.5 1310.6 1095.7 666.5 605.3 386.3 916.8 732.3 238.6 1046 24.7 681.3 973.9 1133.5 264.7 885.1 548.9 864.9 942.7 1082.5 201.1 797 201.5 236.5 511.6 738.8 298.9 267.3 275.6 602.4 384.6 951.3 896.4 419.5 639.7 626 286.3 96 721.2 1084.7 704.3 1202.3 1119.4 968.7 1105.1 606.1 64 1037.1 1180.3 306 1168.9 497.8 1021.4 182.5 616.9

Table 5.7: Samples of chromosomes with fitness values from CS2i3.

Throughput	Time	Chromosome
6197	9280	1 1 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 1 1 1 1 1 0 1 0 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 1 1 1 1 1 1 1 1 1 0 1 0 1 1 1 0 1 0 1 1 1 1 1 1 1 1 1 1 1 0 0 1 1 1 1 1 1 0 0 1 0 1 1 1 1 1 0 1 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 1 0 0 1 1 1 1 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 1 1 1 1 1 1 1 0 1 1 1 1 1 1 1 1 1 1 1 0 1 1 1 1 1 0 1 0 0 0 1 1 1 1 1 0 0 0 1 1 1 1 1 1 1 1 1 1 0 1 1 1 1 1095.9 829 165.4 880.7 272.1 962.5 104.2 550.1 586.1 1189.9 220.8 564.9 1246.6 816.6 671.7 1255.5 260.2 1086.4 884.3 558.5 589.8 1117.9 554.6 755.3 1042.2 144.2 265.9 134.1 547.5 821.9 1091.5 557 993.3 1166.2 214.3 106.5 604.2 584.4 1024.8 1083.5 269.1 1189.8 89.1 1089.7 93.1 1058 277.5 483.4 513.8 2.3 1070.5 1298.7 1215.1 416 114 1079.3 1228.9 528.1 629.8 40.5 1220.1 1026.3 1183.1 1133.9 583.2 87 969.5 529.8 1300.9 901 595.8 104.5 1177.9 591.3 640.2 719.8 759.1 1055.5 329.1 685.3 455.2 671.2 439.6 872.8 303.2 591.1 825.5 390.8 1229.8 683.6 801.1 1262.7 540.7 339.6 90.3 428.1 597.8 4.6 567.1 787.1 701.5 1298.6 1258.7 836.4 514.8 30.8 595 27.1 1243.4 721.9 373.7 1072.7 1020.4 339.1 672.9 303.9 396.3 1040.9 1040.9 85.3 395 708.4 54.4 865.1 324.2 228 114.2 331.6 900.4 264.9 1153.3 429.4 975.8 1189.2 1278.9 1063.5 629.7 1152.9 660.3 1283.6 1230.5 131.5 1099.2 27.5 248.3 242.9 939.2 605.9 66.1 241.5 204.8 380.6 337.5 1322.7 572.4 872.8 60.6 892.6 830.2 370 1147.9 1071.2 1336.7 602.5 221.5 610.5 951.3 1183.9 219.9 765.4 148.8 369.8 761.8 65.7 609.1 816.1 20 934.3 769.2 493.6 1102.8 1147.1 724.1 1157.3 130.8 663.8 1100.9 331.8 1051.1 1228.5 1107.6 188.8 30.8 533.3 1169.4 1130.2 977 196.3 687.7 808.1 95.5 632.9 1048.6 1161.3 903.5 299 664.2 1312.5 170 527.7 343.1 662.7 588 401.5 623.2 1216.5 1193.4 80.8 54 130.3 686.1 86 1190.6 629.6 540.6 4.5 426.3 255.1 801.9 967.8 1107.3 773.1 889.9 578.2 121.9 827 1327.1 338.7 236.4 332.8 983.6 995.4 122.5 865.3 1183 784 246.4 821.7 168.2 1117.9 1194.1 1115.8 57.2 324.6 68.4 1276.6 1293.4 323.4 526.7 68.1 410 344 833.4 211.4 299.9 1251.8 245.2 1047 1042 1139.1
4113.6	6450	0 0 0 0 1 1 0 0 1 1 0 1 0 0 1 1 0 1 1 1 0 0 1 1 0 1 0 1 0 1 0 0 0 1 0 1 1 0 0 0 1 1 1 1 1 0 0 1 0 1 0 0 0 1 1 1 1 1 1 1 1 1 0 1 0 1 1 1 1 0 0 0 1 1 0 1 0 1 0 1 1 1 1 1 1 1 0 0 1 1 1 1 1 0 1 1 1 0 1 1 1 1 0 1 0 1 1 0 1 0 1 0 1 1 0 0 1 0 0 1 0 0 1 1 0 1 1 1 1 1 0 1 1 0 1 1 1 1 1 0 0 1 0 0 1 1 0 0 0 1 1 0 1 1 1 1 1 1 1 0 1 1 1 1 1 0 0 0 1 1 1 0 1 0 0 0 1 0 1 1 0 0 0 1 0 1 1 1 1 1 1 0 0 1 1 1 0 1 0 1 0 1 1 1 1 1 0 0 0 1 0 1 1 0 1 0 1 1 1 1 1 1 1 0 1 1 1 1 1 1 1 0 0 0 1 0 0 0 1 0 0 1 1 0 0 1 1 1 0 0 1 0 1 1 0 1 0 1 0 1 1 1 1 1 0 0 0 1 0 1 1 0 281.2 70.7 1244.5 300.5 458.8 1210.9 648.1 136.7 653.5 404.8 500.9 351.2 740.9 1319.3 319.3 278.2 1238.6 920.4 124.5 383.1 794.6 827.7 986.9 713.5 5.1 986.1 817.2 306.1 990.4 373.1 648.7 1108.6 946.9 88.1 431.7 635.3 1260.2 1327.6 140.7 407.6 317.9 15.2 964.9 129.9 95.6 36.4 7.4 155.5 927.7 999.3 584.7 942.7 668.2 789.8 1308.4 79.1 552.5 257.3 993.8 716.6 887.1 1180.7 1074.6 418.8 1186.8 480 439.2 238.8 802.7 742.3 540.2 719 489.3 166.7 420.9 488.8 1275.3 92.8 503.5 429.3 1327.1 600.3 1168.5 875.6 793.2 681.4 1280.3 1036.9 422.1 1130.6 1255.6 967.2 931.8 1178.9 410.3 1267 1254.5 1197.7 775.6 792.4 1084.5 498.5 573.2 185.3 501 664.6 13.8 60.1 695.1 1168.5 774.9 1108.4 274.1 682 76.7 792.8 669.8 984.9 936.2 313.3 482.4 581.8 413.3 146 923.6 93.5 684.2 291.8 1300.6 927.5 589.1 220.8 180.7 777.2 986.8 508.2 788.8 1253.6 1017.8 543.5 927.6 766 871.6 813.6 702.3 797 781.5 1315.7 1133 499.7 397.6 380.1 505.9 1262.2 739.3 487 225.1 1131.9 779.3 205 984.1 487.1 1087.9 73.3 1109.5 1272.3 1270 499.5 881.2 1038.9 209.6 1081.4 346.2 66.7 227.7 1081 691.9 468.8 449.9 6 268.3 1004.9 337.6 483.5 774.4 762.8 1317.3 1260 1135.2 404.8 1198.7 311.2 739.7 334.2 532.8 821.6 851.6 411.6 500.2 1226.3 848 1101.1 1202.4 380.8 1136.3 115.9 689 899.4 153.3 1266.5 1323.3 899.7 1254.8 103.1 57.6 754.4 1324.3 1169.2 940.4 1314 993.3 1049.9 663.2 428.6 1192.6 464.9 1080.4 1159.8 1228.4 32.9 780.4 1164.8 557.5 1103.7 230.4 1064.1 73.8 858.4 1173.4 94.9 216.1 24.3 1314.1 1162.8 45 372.1 709.3 652.6 606.6 348.1 391.1 486.9 1258.2 988.7 1075.1 65.7 1328.3 410.2 406.5 1159.9 497.1 1227.9 673.6 873.3 928.9 184.6 359.8 150.5 36.1 911.1
42	350	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 1189.1 807.8 80.3 146.9 1042.2 1064.3 670.9 1070.8 1160.2 610.1 647.7 971.5 80.6 84.9 879.3 7.7 956.2 279.1 268.9 183.9 1195.6 239.6 802.7 258 488.6 787.8 1260.1 296.4 501.6 1259.8 1044.5 125.5 1050.1 448 122.8 439 657.7 821.4 408.3 396.9 1233.1 103 622.1 1101.3 553.2 1191.3 319.6 757.7 1181.3 39 916.2 1284.7 879.3 1086.8 733.7 1159.1 146.1 501.8 888.8 1148.3 597.5 345 262.3 535.2 222.3 389.7 1264 711.8 858.3 663.3 493.9 614.8 1005.9 49.9 578.5 1120.1 364.7 55.1 1035.7 863.2 542.1 506.7 159.7 767.5 52.3 1089.9 1095 917.7 1181.6 926.9 1165.9 704.8 997.2 920.9 440.5 452.5 520.9 440.8 1185 264.9 1269.1 1109.1 561.1 167.8 114.3 104.1 446.7 719 254.7 869.6 828 1231.6 328.9 174.6 18.9 957.7 518.2 34.3 696.9 314.8 674.1 764.9 150.4 705.7 150.6 625.8 741.1 1180.2 344.2 129.5 483 169.3 781.6 384.7 1339.1 1232.5 43.5 1065.9 957.7 966.6 174.1 827.7 575.3 357.2 473.9 1237.6 494 1279 623.3 534.1 937.6 418.6 834.7 110.6 1174 672.4 330.6 1147.6 850.2 90.2 1116.3 447.1 555.6 617.5 1306.1 1230.9 918.2 330.3 1050.7 1125.9 807.7 558 119 978.8 207.5 879.1 715.2 1012.3 104.9 1227.2 1040 279.7 1024.2 448 1289.7 379.1 706 18.3 821.1 893.8 676.2 666.4 187.6 237 139.8 346.2 420.1 1274.4 549.8 1.4 343 1271.9 1177.9 1176.4 205 1064.2 417.5 844.8 569.3 634.5 365.1 1214.5 831.6 1084.2 145.4 170.3 452.7 700.3 1026 392.1 1079 905 502.1 751.1 1153.2 1061 370.7 1161.7 299 373.8 450.3 468.9 1092.5 553.7 510.5 1165 961.3 1293.4 829 1173.9 851 1333.7 385.7 770.5 50.5 1046.1 1099.2 1228.4 806 1180.3 872.5 363.3 418.1 748.4 1005.6 88.5 104.5 823.7 208.5 1156.8 940.9 1244.9 912 425.9 287.1 374.6 470.1 312 640.7 643.2

Table 5.8: Samples of chromosomes with fitness values from CS2i4*1.5.

Throughput	Time	Chromosome
6179.3	9670	1 0 1 1 1 1 0 0 1 0 1 0 0 1 1 0 0 1 1 1 1 1 0 1 1 0 0 1 0 1 1 0 1 1 1 1 1 0 1 1 0 0 0 0 0 1 0 0 0 1 0 1 1 1 1 0 1 0 0 0 0 0 1 1 0 1 1 1 1 1 0 0 0 0 1 1 0 0 1 0 0 1 1 0 1 1 1 1 1 0 0 0 0 1 0 1 1 1 1 1 1 1 0 1 1 0 0 1 1 0 0 0 0 0 1 0 1 1 1 1 0 0 1 0 0 1 0 0 1 1 0 1 1 1 1 1 1 0 0 1 1 0 0 1 0 0 0 0 1 1 1 1 1 0 1 1 0 0 1 0 0 1 0 0 1 1 1 1 1 1 1 1 0 0 0 0 1 0 1 1 1 1 1 1 0 1 1 0 0 0 0 1 1 1 1 1 1 1 0 0 1 1 1 0 1 0 0 0 0 0 1 0 1 1 0 1 1 0 0 1 0 0 1 0 0 1 1 0 1 1 1 1 1 0 1 1 0 0 1 0 0 1 0 0 1 1 0 1 1 1 1 1 0 0 0 0 1 0 1 1 1 0 1 1 1 1 1 1 0 1 0 1 0 0 1 1 0 1 1 1 1 1 1 0 1 0 1 0 0 1 1 0 1 1 1 1 1 1 0 1 0 0 0 0 0 0 1 0 0 1 1 1 1 0 1 0 0 0 0 0 1 1 0 0 0 1 0 1 1 1 1 1 1 1 0 1 0 0 0 0 1 1 0 1 1 0 1 1 0 0 1 0 0 1 1 0 0 0 0 0 1 1 0 1 0 1 0 0 0 0 0 1 1 0 0 1 1 1 1 1 0 1 0 0 0 1 0 0 0 0 0 1 1 1 1 0 1 1 0 0 1 0 0 1 0 0 1 1 1 1 1 0 1 1 0 0 1 1 0 0 1 0 1 0 1 1 1 1 1 1 0 1 0 0 0 0 0 0 1 0 1 1 1 71.3 469.3 175.9 977.6 566 1050.6 824.1 755.5 1299.1 1157.4 1248.1 602.8 875.4 613.9 519.4 271.3 1192.7 150 1002.2 345.4 86.1 826.9 962.2 1320.6 935.6 315.9 1214.6 1140 616.6 25.9 1315.4 220.6 964.5 1337.2 1133.3 1318.5 18 274.6 337.5 1145.2 1064.4 681.8 252 381.8 135.8 584.5 1310.1 103.4 808.9 687.6 983.1 1130.4 591.5 532.8 888 234.8 1230.1 730.9 250.4 861.1 528.3 445.7 335.5 552.8 920.6 651.8 1339.2 375.9 488.2 1129.4 497.4 919.6 274.5 204 717.5 256 1107 331.3 1131.2 215.7 44.6 1098.7 1077.4 310.5 456.4 46.4 143.7 272.3 678.7 4.2 1187 616.2 814.7 1206.9 367.2 750.3 1117.8 1204.3 906.7 735.5 401 821.5 409 490.7 856.5 1264.3 1188.5 634.3 1320.9 1207.3 743.7 1060.9 985.4 662.2 1203.3 188 487.7 843.3 390.9 370 702 894.8 1195.9 878.5 1158.1 973.4 166.3 1299.9 407.5 905.7 99.8 486.6 562.4 406.3 778.4 442.4 54.9 1110.4 894.6 1025.6 254.7 297.6 88.2 1.2 988.6 840.9 936.5 178.9 1296.4 621.7 223.5 1211.2 580.4 634.5 253.5 788.3 1257.1 598.8 890 383.5 337.3 156.7 218.8 183.8 530 260.1 772.1 806.4 380.5 829.4 451.2 227.9 855.9 279.9 1292.1 1317.3 70 404.6 22.2 1090.6 481 753.4 1039.2 1029.2 1082.9 610.1 431.4 359.9 86.8 1154.2 161.5 779.4 1119.1 18.7 1107.1 640.6 1086.5 1181 1057.6 1245.9 820 589.5 151.2 500.3 592.5 1160.2 230.7 1064.1 1087.6 454.3 1311.6 1177 1130.1 1181.9 208.7 926.4 561.7 341.3 548.7 55 271.2 652.9 719.6 1249.5 50.9 636.1 1231.5 97.7 732.5 711 1221.5 1040.6 764 178.6 82 971 821.7 675.6 1285.5 1032.4 449.5 837.7 1044.9 861.2 917.3 370 1313 640.1 1171.2 44 1313.4 358.5 1302 264 738 109.8 1003.7 173.9 499.5 122.8 274.3 801.8 1045.1 471.4 713.5 1021.6 294.4 339.7 1174 870.9 361.7 794.5 95.7 511.2 935 699.8 670.5 282.3 64 798.2 653.4 87.8 761.3 1198.3 1333.5 345.3 218.1 307 628.1 316 1274.6 1255.3 368.2 206.6 918.3 1315.7 877.4 16.4 576.3 1128.8 1223.1 619 765.1 755.2 1254.1 1197.5 1010.1 963.9 316.1 412.1 594.9 9.7 295.6 985.9 405.8 819.5 1 104.1 245.2 744.3 1230.5 506.2 720.8 867.7 1060.8 930.4 722.9 403.6 618 661 510 509.8 1306.9 5.1 66.9 199.6 1123.2 1108.5 807.5 436.4 1228.7 278.3 1270.4 854.6 624 223.8 677.4 1031 723 952.3 60.2 624.4 1041.7 444.6 473.2 1103.4 111.9 286.2 1172.4 276 921.6 1259.4 674.8 936.5 737.9 536.7 257.9 979.6 137.9 1256 479.1 559.7 642.2 758 356.2 1126.5 214.4 863.6 366.5 62.2 306.8 557.2 624.4 892.2 984 414.4 1259.8 1329 76.7 1268.4 88.7 711.3 251.2 1267.5 1302.6 921.3 1003.7 557.1 50.4 653.2 681.4 427.8 1037.8 843.1 612.4 439 99.6 725.5 893.4 67.2 841.9 330.8 1073.1 832 1181.5 232 83.4 635.4 136.3 307 370.9 937.9 671.7 955.2 954.8 642 811.7 449.3 344.3 402.4 706.8 305.4 68.1 501.7 53.8 1278.2 452.5 199.9 859.1 623.7
4186.3	6150	0 0 0 0 0 0 0 0 0 0 1 0 0 1 1 1 0 1 1 1 1 1 1 0 0 0 0 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 0 1 1 1 0 1 0 0 0 0 0 0 1 1 0 0 0 0 1 0 0 0 0 0 1 1 0 1 1 1 1 1 1 1 1 0 1 1 1 1 1 0 0 0 0 1 0 0 0 1 1 0 0 0 0 1 1 1 0 1 0 1 1 1 0 0 0 1 1 0 1 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 1 0 1 1 0 0 1 1 0 1 1 0 1 1 1 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 1 0 1 0 0 1 0 1 0 0 1 0 0 1 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 1 1 1 0 1 1 0 1 1 1 0 0 0 1 0 1 0 0 0 0 0 0 0 1 0 1 0 0 0 0 0 1 0 1 0 0 0 1 1 1 1 1 0 1 1 1 0 0 0 0 1 1 0 0 0 0 0 0 0 0 0 0 0 1 0 0 1 0 0 0 1 0 0 0 0 1 0 1 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 1 0 1 1 0 0 1 0 0 1 0 1 1 1 0 0 1 0 0 1 0 0 1 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 1 0 1 1 0 1 1 1 1 1 1 0 0 1 0 0 1 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 1 1 0 0 1 0 1 1 1 1 0 1 1 1 0 1 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 1 0 0 0 1 1 1 0 0 1 1 0 0 0 0 0 0 0 1 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 7.1 566.5 1141 4 405.1 906.7 1083.4 434 670.5 1261.6 547.9 677 1256.1 276.7 879 1010.6 136.2 1147.2 1277.1 464.8 725.3 781.8 155.4 14.9 508.4 176.3 805.4 336.4 392.8 1333.8 1046.1 23.7 181.4 301.6 278.6 89.6 753 549.2 836.6 90.1 1045.7 1219.5 192.7 551.5 504.2 1085.6 596.7 80.5 221.6 833.6 1048.4 418.3 441.8 942.7 149.1 1181.4 829.6 361.7 743.4 170.7 139.5 699.6 381.1 334.7 6.9 585.6 443 107.2 26.9 950.5 1069.4 72.8 32.2 719.5 313.3 974.6 939.2 462.8 1302.4 334.6 915.8 533.2 112 756.8 289.1 28 1197.4 491.7 1073.2 1258.3 359.4 771.7 942.7 231.7 1310.4 75.6 1271.4 4.2 858.2 1229.3 1117.9 924.4 267.6 167.5 968.2 1083.6 364.2 840.1 591.6 107.6 1238.6 399.8 250.1 272.9 224.1 863.9 398.2 615.8 828.8 278.8 768.4 777.9 855.2 81.1 117.9 1161.2 106.5 396.6 329.3 1077.6 675.2 581.3 315.2 928.5 640.5 519.4 1329.8 77.4 315.7 1193.5 1283.7 486.5 142.4 1156.9 300.6 32.8 874 462.8 916.7 807.3 497.8 1011.8 365.9 494.2 664.2 294.5 944 728 1047.3 1192.4 9.6 515.7 18.4 318 1051.5 1247.8 529.3 989.2 882.5 756.7 48.1 541.7 1233.4 1072.8 803.9 441.4 779.7 1032.6 189.3 990.8 238.5 1336.2 426 122.2 834.6 1314.6 390 906.3 1083 329 128.7 199.8 1009.3 544.3 563 760.5 1262.6 134.8 57.2 616.7 967.2 1255.2 1048.5 1231.8 930.3 220.7 830.5 433 1003.9 335 525.1 217.9 347.4 475.7 1197.8 1184.2 680.9 1248.1 720.2 706.1 899.9 210.7 235.4 1044.2 1127.6 921.6 662.9 898.3 1290.8 829.1 63.1 268.7 971 245.1 895.7 674.5 29.3 175.4 895.1 799.4 199 372.4 1121 470 277 403.9 1150.4 114.1 181.4 60 149.1 345.9 478.8 662.7 129.2 39.1 914.6 1058.3 745.9 1312.7 853.8 827.5 1199.5 103.2 1135.8 232.3 670.2 492.9 794.1 62.7 1159.1 304.3 950.4 322.9 335.2 28.5 377 1256.8 998.1 1251.1 152.1 223.2 1325.3 1123.4 145.2 685.8 917.4 920 618.8 532.2 550.5 1300.4 80.2 311.8 500.5 1010.7 1265.5 458.3 726 30.4 1066.2 1144.1 820.2 441.6 1176.6 548.1 750.6 860.6 838.3 736.5 87.1 943.1 358.7 127.4 532.4 243.9 704.8 827.5 783.7 559.6 952.2 1046.3 923.6 322.4 94.4 600 837.6 800.3 439.2 1225.4 997.9 617 936.4 1044.3 128.1 939.1 1321.8 1005.3 354.3 1205.5 1073.4 542.7 687.8 1001 1042.8 126.6 481.8 12.6 1064.5 1258.3 1308.1 216.4 866.6 556.7 112.5 778.2 289.9 865.7 135.2 923.8 1319.8 986.1 1067.8 1128.5 1171.5 55.5 1269.3 140.4 509.5 1179.1 1022.9 1328.6 482.4 991.9 290.1 1275.9 52.8 1255 287 726.2 112.3 273.4 1095.3 301.3 388.9 639.4 633.7 44.1 348.6 1095.7 783.4 397.6 507.9 415 423.9 1092.9 864.5 341.5 695.7 1216.1 487.1 535.3 498.8 995.2 745.3 1212.1 302.3 342.6 748.8 753.8 940.2 512.8 152.4 98.4 1299.9 750 765.5 511 886.1 1305.6 683 1289.8 792.4 284.1 1123 1121.1 1079 1077.1 1113.9 1327.8 34.8 756.9 529.1 351.8 890.1 464.8 861.2 1164.8 773.8 415.3
61.6	240	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 1 0 6.9 108.7 1141 4 374.8 901.5 1089.5 434.1 663.3 1048 478.4 1006.8 1257.6 346 994.5 1035.3 171.6 1177.9 1312.7 405.1 725.3 887.1 171.5 114.1 33.7 65.7 805.7 336.4 686.2 551.4 125.9 8.5 193.7 281.5 275.3 90.1 753.2 683.7 861.2 92.8 1138 1196 1182.8 553.1 499.1 659.8 596.9 11.3 888.6 251.7 374 200.1 442.1 942.7 1203.7 1160.7 829.6 322 743.4 170.7 654.9 672.4 390.1 332.1 4.6 565.7 265.4 1257.6 1150 507.7 795 72.6 28.2 716.4 313.3 513.5 682.5 460.9 1329 339.1 915.8 531.6 78.3 751.6 266 27.6 1197.4 491.7 1073.1 1259.6 362.1 752.9 946.6 236.5 1311.2 75.6 1272.6 7.6 624.8 1201.7 117.3 922.9 294 210.9 712.5 1229.2 366.1 395 601.8 71.8 514.3 950.9 250.2 272.9 801.1 864.9 718.6 615.7 713.4 818 784.9 776.8 857.4 82.4 116.6 1161.2 1101.9 498.6 329.3 1077.7 760.8 616.6 305.6 942.3 632.9 518.4 1330.8 1194.3 317.6 1252.3 1319.7 380.9 138.7 1118.6 267.5 33.4 868.2 403.6 917 807.3 497.3 1011.8 342.3 499.6 680.4 294.5 944 729.2 1045 1175.7 3.1 495.3 817.1 318 128.8 1249.8 530.4 989.4 914 1189.3 44.2 994.6 1304.9 1067.5 0.5 622.9 773.2 1032.6 191.7 858.1 238.5 1336.2 349.4 122 793.4 1314.6 390 208.5 1082.6 329.4 78.4 175 1009.3 545.1 538 1072.5 1240.9 134.9 53.6 726.5 953.6 691.5 1018.2 1227.4 930.7 217.3 830.9 1088.4 1003.8 335.4 526 159.2 354.7 483.5 1197.8 1182.6 736.4 1237.6 733.6 1127.4 836.2 245.8 234.7 1057.3 1114.1 273.9 661.8 889.3 931.1 839.4 63.1 1118.4 974.1 333.7 895.7 673.7 29.3 175.7 126.7 799.4 524.8 368.7 1133.5 394.1 278.7 403.4 1105.8 113.9 796.4 57.6 148.6 1156 433.4 662.7 132.5 39.1 876 38.4 683.3 1339.9 332.9 829.3 1199.3 158.4 1023.1 242.6 670.2 493.6 794.1 896.1 258.2 306.7 949.9 485.5 372.7 26.7 142.9 1256.8 998 1251.3 108.2 219.8 1327 1123.5 401 685.7 917.1 714.2 334.6 507.2 545.3 1275.4 90.5 449.9 500.5 1010.6 1222.8 433.9 146.8 70 1064.2 1146.4 940.1 552.2 1176.6 548.1 237 859.8 352.6 794.2 87.1 677.4 357.8 126.4 539.1 243.9 704.4 1265.6 784.1 559.8 1077.9 1009.3 907 477.7 749.2 639.7 838.1 770.4 439.2 103.8 981.7 621.2 651.5 1049.8 1203.5 939.1 1333.4 1005.3 461 1204.8 1050.9 533 689.5 959.1 1040.6 126.1 1127.4 12.6 1059.2 1260.4 158.9 240.5 922.9 616.8 112 781 289.7 522.7 358.2 923.8 1325 988.2 1049.1 1102.6 1183.4 39.1 281.2 143.5 461.1 1327.9 1022.9 619.3 482.5 793.8 406.7 163.5 52.2 1256 287 444.3 112.3 974 1103.5 302.6 385.6 639.1 418.5 29.9 244.8 1051.7 215.3 398.2 487.9 415.5 422.1 1099.1 861.5 341.6 706 1203.4 349.9 533.5 214.8 992.5 745.4 1211.9 1286 338.2 764.8 751.9 851.7 491.2 150.6 86.1 1180.9 749.9 765.9 511 735.4 131 1032.4 1257.7 792.4 246.6 1128.3 602.4 1014.9 649 1336.5 1327.8 50.1 757.1 533.9 365 892.7 464.8 863.8 1219.5 777.2 401.9

Table 5.9: Samples of chromosomes with fitness values from CS2i4*2.

Iteration	Throughput	Stock	Chromosome
i3	62781.7	742	612.9 556.6 565 151.1 606.2 554.7 670 566.4 268.5 584.3 588.9 566.6 609.8 637.6 564.6 592.4 646.2 647.9 623.6 656 611.7 595 562.7 615.6 557.3 595.9 471.9 584.8
i3	61909.2	752	509.3 516.2 578.3 603.5 509.7 582.7 591.2 510.2 612.4 511.3 658.3 526.7 580 593.9 640 578.4 562.3 591.8 570.1 522.6 538.1 592.8 579.6 616.3 585.3 622.2 655.4 283.2
i3	59914.6	529	670.0587609171424 666.8 580.3 544.4 561.7 603.2 646.8 578.9 671.6 582.3 644 655 578.1 580.5 558.4 652.6 609.7 595.9 551.3 638.3 668.5 562.3 549.8 311.2 634.9 543.7 582.5 544.8
i4*1.5	62711.7	569	0 0 0 1 0 1 0 1 1 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 658.7 307.3 498 148.4 427.4 162.6 133.5 643.4 70.6 564.7 211.2 582.6 615.8 193.4 332.9 190 600.9 149.5 428.3 267.1 478.2 568.1 231.8 611.8 8.8 237.3 0.4 296.3 45.7 603.5 38.2 88 387.9 297.3 107.9 67.6 271.2 370.9 41.4 242.6 137.7 485.7
i4*1.5	61913.6	435	0 0 0 1 0 1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 353.7 341.9 395 43.6 518.7 348.3 125.1 209.7 171.1 580.2 319.7 514.7 169.3 211.8 515.3 12 194.7 270 265.6 455.4 45.9 303.7 415.1 613 344.7 27 118.4 315 544 592.4 594.7 112.3 443.6 22.9 405.2 217.3 233.2 319.3 279.9 208.2 15.6 512
i4*1.5	52817.9	276	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 488.8 538.8 591.6 43.6 538.2 254.3 124.7 152.1 181.7 585.5 319.7 531.5 169.1 61.8 509.2 3.3 530.8 270.5 299.3 454.3 48.7 103.7 412.4 601.8 344.7 14.4 118.4 18.8 266.8 165.9 332.3 109.7 296.3 8.1 335.3 211.5 229.5 317.9 287 219.7 15.7 62.6
i4*2	62691	442	0 0 0 1 0 0 0 1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 323.6 405.6 282.8 251.7 189.4 440.9 50.6 62.8 254.7 383.6 51.9 209.3 322.5 609.6 351.1 184.3 437.4 436.5 471.4 582.9 569.8 334.9 345.3 475.8 36.6 288.2 148.1 225.4 140.6 413.4 185.8 198.6 47 406.5 370.5 422.1 347.1 96.6 567.6 103.9 640.8 326.1 655 217.9 329.5 431.1 632.5 257.6 326 648.2 362.3 55 180.5 447.7 440.5 246.6
i4*2	61904.6	477	0 0 0 1 0 0 0 1 1 0 0 0 0 0 0 1 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 615.3 69.8 242 226.4 118.5 215.8 610.3 524.8 293.4 93.5 284.8 586.3 174.1 629.8 152.1 600.8 509.3 660.4 277.2 283 233.1 295.9 480.4 437.6 226 603.7 294.7 172.6 491.6 145.4 639.9 84.6 269.4 173.2 246.6 454.6 138 559.2 173.2 655.7 580 112.6 435.1 425.5 291.6 5.5 147.8 656.8 132.7 563.3 263.3 162.9 205.7 240.5 225 235.6
i4*2	52016.8	276	0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 12.3 256.2 43.2 277.8 132.5 324.5 366.7 562.7 386.9 494.8 469.1 552.3 575.5 267.4 120.3 91.2 235.1 491.3 415.2 522.1 617.9 309.4 144.1 31.3 471.8 528.3 599.2 597.3 211.1 400.5 182 431.1 430.2 438.1 493.1 415 41.8 613 662.5 507.2 627.2 481.2 465.9 193.7 474.8 421 337.7 451.4 181.9 462.8 330.5 94.5 633.8 87 606.8 432.4

Table 5.10: Samples from Pareto front, case study 3.

production system and the implementation of relationships between these elements, this model may be stated as a generic simulation model of a large production area.

Table 5.10 shows three samples for CS3i3, CS3i4*1.5, and CS3i4*2. Each of these three samples belongs to Pareto front of 100th generation. The sample shows fitness values and related chromosomes.

Sub-system – experimentation level. The optimisation dynamics of each case study are presented in Figure 5.12 by plotting initial, 20th, 40th, 60th, 80th and 100th generations. Within one set of experiments, different simulation models showed different Pareto-frontiers. The same models resulted in different patterns of the Pareto-frontiers in the different sets yet share some similarities in the patterns.

Table 5.11 shows optimisation results of CS2i3 with the maximum throughput, minimal time, and the chromosome resulted fitness values out of the Pareto front.

The convergence test was performed by (i) testing the dynamics of the main experiment body in Figure 5.12, (ii) testing the dynamics of the convergence test's experiments in Figure 5.13, and (iii) comparing 500th generation with 100th generations of the main experiment body as shown in Figure 5.14. The 500th populations were no better than the 100th populations in two case studies out of three for Iterations No 3 and No 4; case study No 2 was not converged within 50'000 evaluations. The convergence test of case study No 2 was not continued further than 50'000 evaluations because the optimisation system crashed shortly after this number.

The last generations of both Iteration No 3 and No 4 were plotted in Figure 5.15 for comparison. Each diagram in this figure contains three colour-encoded groups of results. Iteration No 4 dominated Iteration No 3 in case studies No 1 and 3. Case studies No 2 and 3 showed that Iteration No 4 *1.5 results have minor differences to Iteration No 4 *2 results, while Iteration No 4 *1.5 showed clear domination over Iteration No 4 *2 in case study 1.

The results of the experiments should prove or fail the hypothesis of simultaneous optimisation of production plans and schedules. Firstly, it must be optimised, and Figure 5.12 shows the optimisation in dynamics. Secondly, for the benefit of the analysis, the results should pass convergence check, and Figure 5.13 and Figure 5.14 provide plots for this check. Thirdly, Iteration 3 with Iteration 4 must be compared with each other, and Figure 5.15 provides plots for this analysis. Together, this validates the sub-system level of the experimentation part of the research.

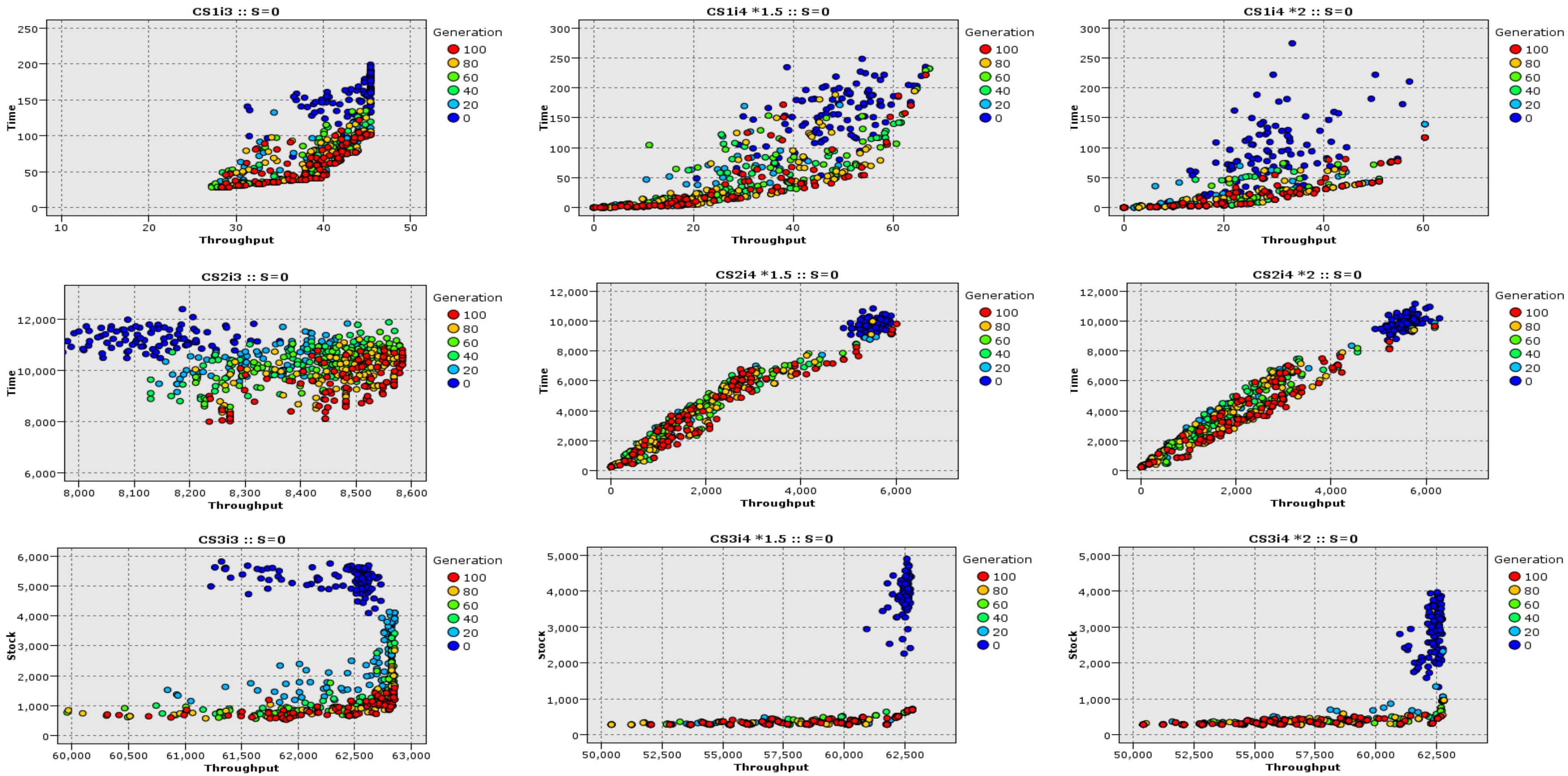


Figure 5.12: Output results for all case studies performed. Each graph contains initial, 20th, 40th, 60th, 80th, and 100th generations; generations are colour encoded. The first column of the diagrams represents i3, the second – i4 *1.5, and the third – i4 *2.

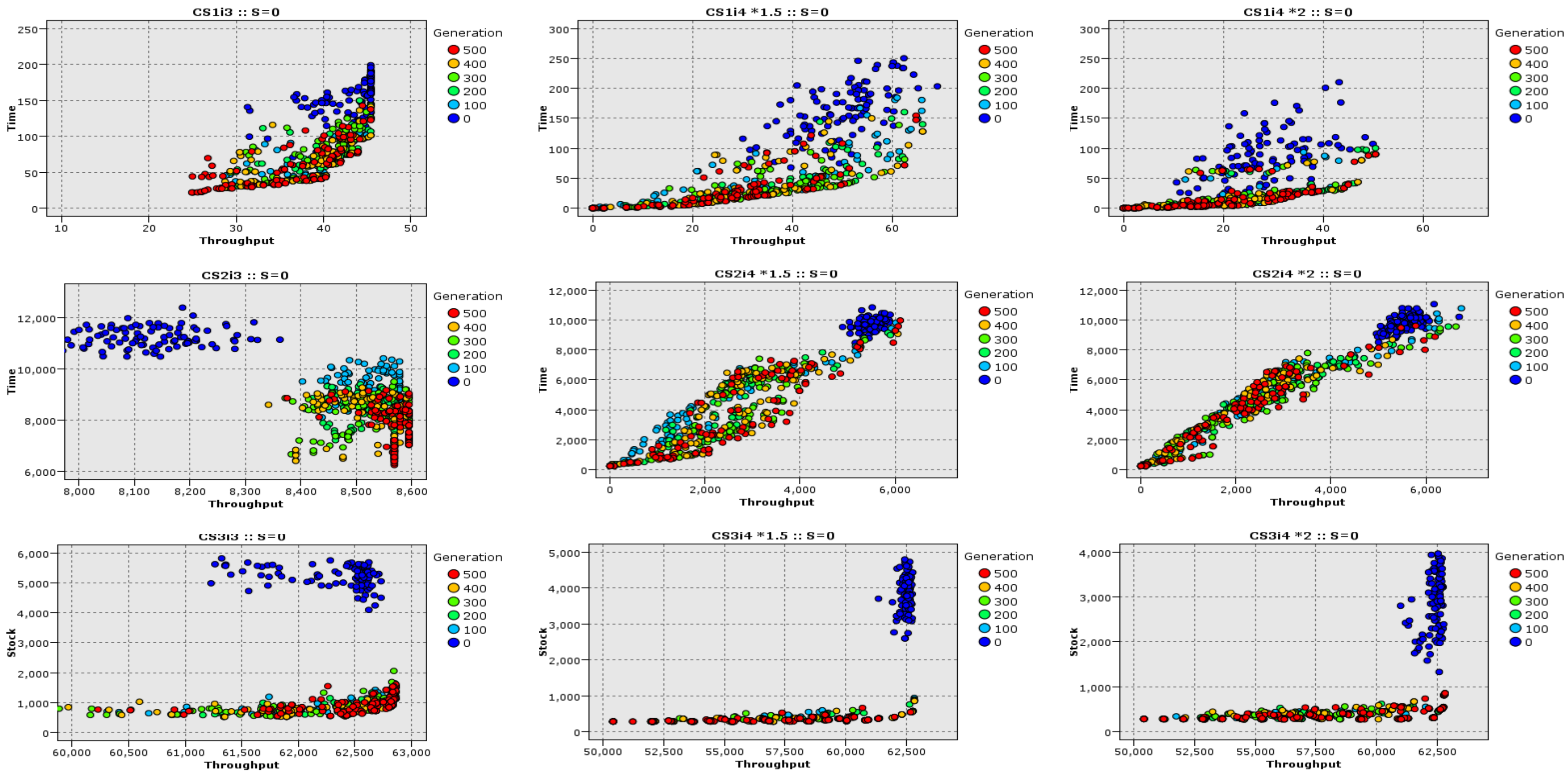


Figure 5.13: 500th generation for all case studies. Each graph contains initial, 100th, 200th, 300th, 400th, and 500th generations; generations are colour encoded. The first column of diagrams represents i3, the second – i4 *1.5, and the third – i4 *2.

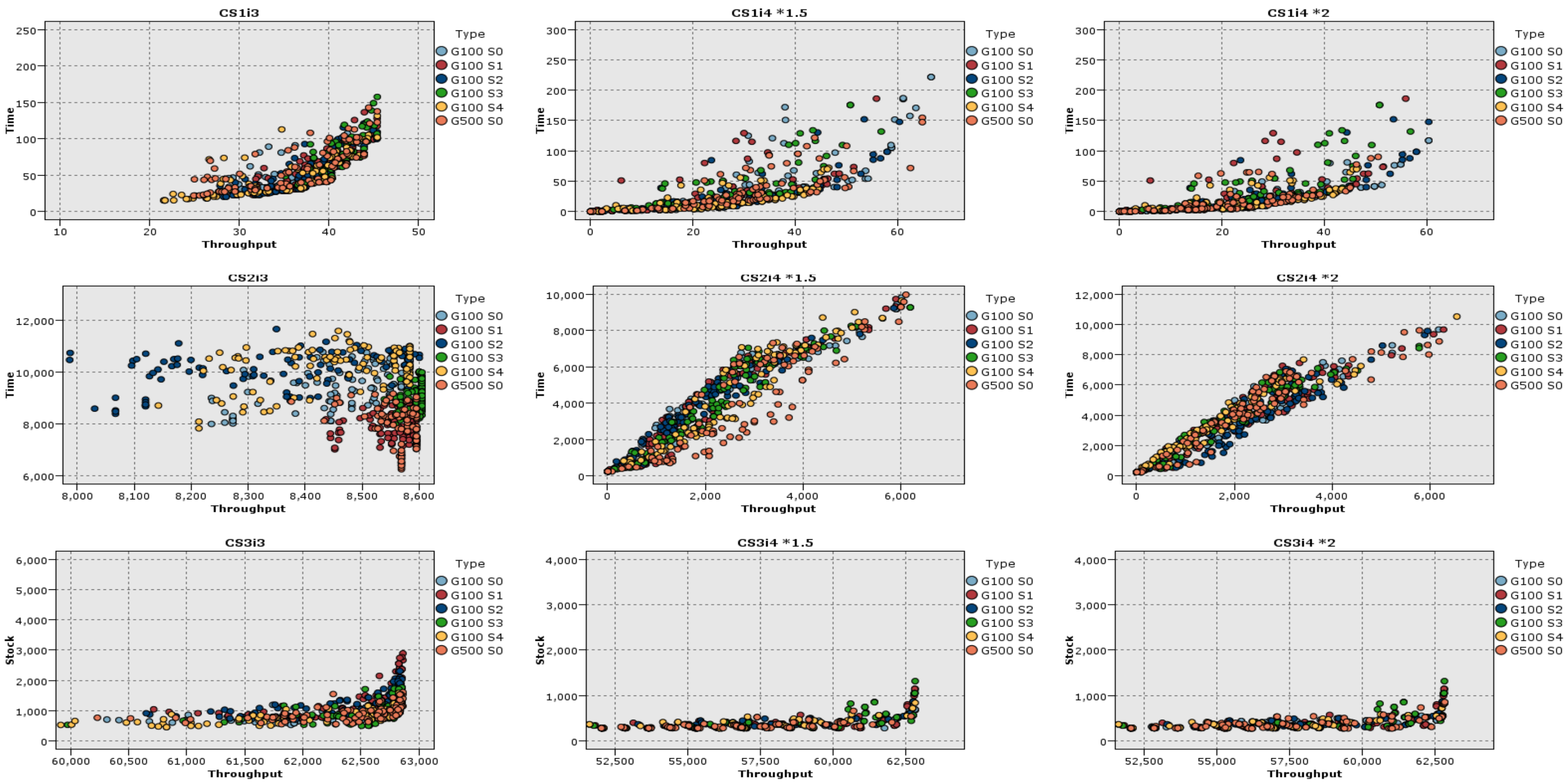


Figure 5.14: Last population of both main and convergence check' experiment bodies. G100 S0 means 100th generation with random seed 0. The first column of diagrams represents i3, the second – i4 *1.5, and the third – i4 *2.

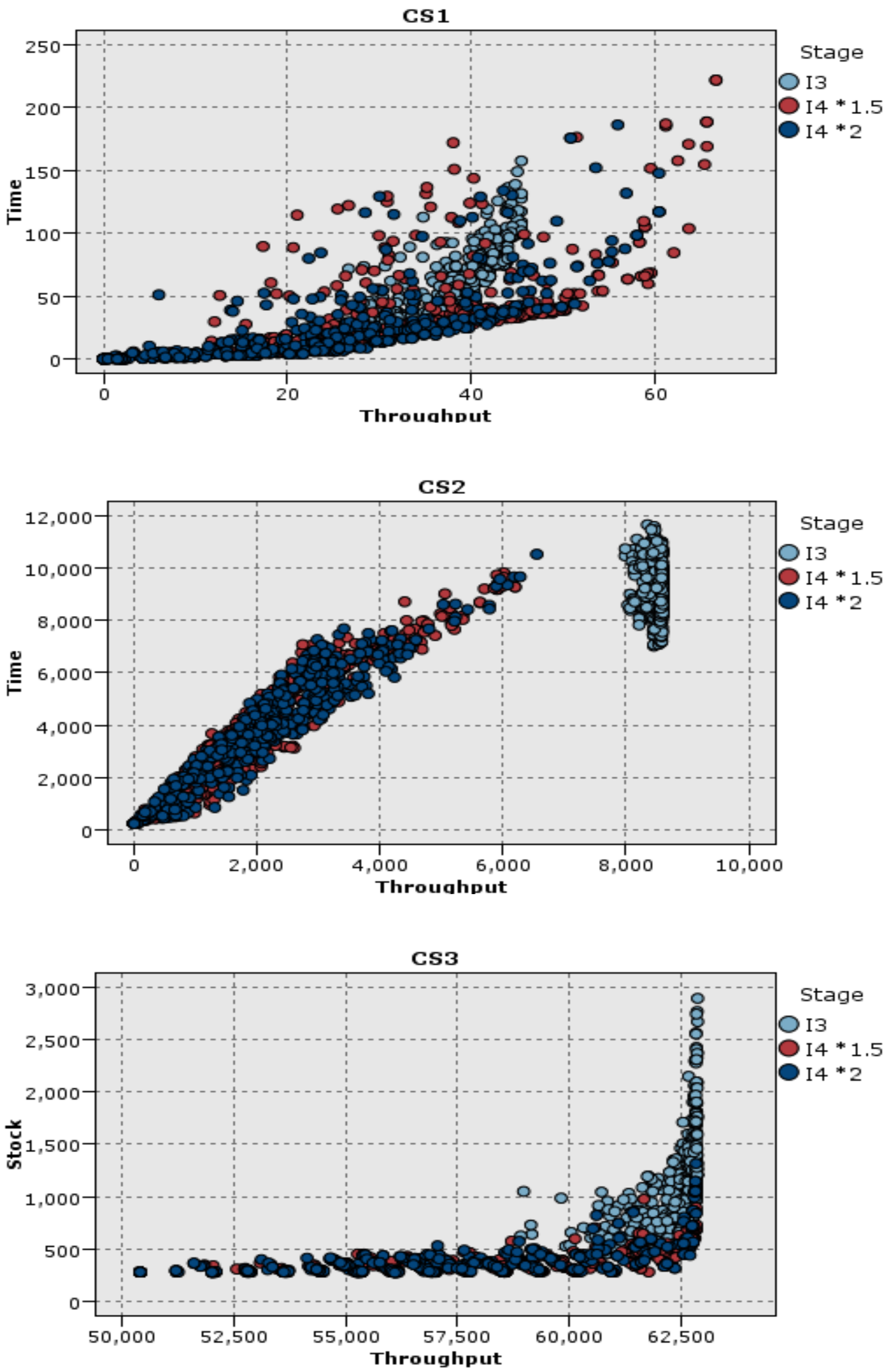


Figure 5.15: Comparison of i3 with i4, each colour-coded group represents the final populations; I3 for i3, and I4 for i4.

Throughput	Time	Chromosome
8583.5	10220	134.6 1271.4 1298.7 817.4 979.9 741.8 619.1 403.5 208.9 734.2 400.8 328 1106.3 930.5 216.1 699.1 644.8 682.8 226.4 914.9 322.9 29.6 376.2 874.1 508 320.2 1121.6 61.9 1239 778.5 267.1 903.1 245.5 270.2 695.4 1083.9 1168.3 553.9 241.8 350.5 935.1 1171.6 540.9 1276.3 814.1 90.4 213.3 177.4 1220.5 961.5 961 940.8 626.4 59.4 460 1070.2 914.3 954.6 338.4 266.2 960.3 885.3 929.4 1303.4 1061.9 1080.2 655.5 959.1 1283.4 558.6 305.5 1005.2 323.4 492.4 825.1 915.7 608.8 1200.3 36.9 932.3 434.9 526.2 542.3 223.2 384.3 919.5 150.2 1140.4 664.8 88.6 4 943.5 483.9 1063.5 603.2 444.4 509.5 1220 489.6 503.3 1257.2 997.9 1063.9 499.8 432.1 594.8 1026.2 274.3 134.5 1249.8 1225.2 276.2 990.3 121.8 515.1 286.7 771.7 882.4 692.5 972.3 48.6 1145.6 1016.5 85 1020.4 265.8 784.9 1056.6 1260.1 1031.9 1213.5 324.8 440 557.8 1309.1 1128.8 266.3 85.7 1064.4 529.6 458.2 65.7 182.9 839.6 485.3 294.6 162.8 309.3 1036.3 581 956.6 1068.5 1080.5 256.7 280.3 1032 847.7 536.6 273.1 1210.4 62.5 346.1 163.8 818.6 314.7 70 836.2 624.8 515.4 563.3 642.2 239.6 707.1 497.5 504.2 67.5 1242 713.1 822.8 1098.1 213.5 1008.7 377.6 120.3 270.6 981.9 282 432.3 634.8 889.7 948.9 1204.5 315.9 321.5 637.6 936.6 194.9 713.7 466.7 614.1 1285.3 1003.3 597 654.1 530.9 299.9 963 216.5 608.1 1193.1 714.4 286.7 499.1 946.3 963.4 625.3 224.2 900 703.3 1023.8
8444.6	8110	143.1 1258.9 1292.6 799.4 930.4 1179.2 484.8 998.8 201.3 1276.3 407.5 290.4 964.1 502.1 217.2 388.4 503.2 332.6 247.5 767.2 288.5 62.3 211.3 1198.2 155.4 1005.5 1125.2 23.5 178.6 39 273 906.2 433.7 201.9 681.1 761.3 952 414.3 887.7 615.6 622.9 896.4 192.6 1285.4 191.7 1081.4 213.3 897.9 1251.1 911.6 983.2 579.2 790.1 224.1 518.3 1062.7 889 911.6 517.1 1052.1 960.7 921.8 938.6 479.7 1251.8 974.6 38.1 915.6 1256.7 1071.5 299.9 933.3 316.5 477.6 1098.1 945.2 964.6 652.6 1040.9 887.2 460.7 448.5 525.8 221.9 284.7 338.3 1093.3 957.3 508.9 973.4 296.1 1080.2 1152.1 1089.5 596.6 493.3 526.6 1217.3 275.9 500.4 361.2 812.3 469.3 912.9 885.9 1002.6 601.3 525.9 959 960.9 1211.2 307.9 959.2 130.1 466 375.1 1238.9 1335.7 402.4 609.8 992.1 1255 989.4 717.6 986.9 996.4 764.5 1056.8 1201.6 410.9 333.4 295 486.9 935.6 1277.3 204 951.8 64.3 1119.4 1190.8 622.1 1229.4 439.5 1044.3 322.2 576 117.3 1002.5 609.1 507.2 319 150.3 1093 605 961.7 1068.4 1242.7 582.9 1101.6 160.5 68.1 347.5 1247.8 1101.9 282.4 124.8 815.9 635 1251 628.5 494.4 408.6 748 1036.8 495.8 28.4 1246.1 136.9 637.5 1078.3 405.7 370.4 329.1 900.9 326.5 1009.8 607.1 951.3 1004.6 199.7 949.2 1225 1075.4 317.1 888.6 898.7 192.1 675 1192.7 372.9 1249.3 649 1274.1 645 520.4 223.3 966.9 216.2 625.4 1175.9 169.5 1054.6 922 935.2 981.9 631.9 922.5 1183.2 637.7 1084.7
8291.6	10080	290.7 1259.2 1284.8 790.9 902.1 1179.5 619.2 1019.8 208.8 1016.9 406.6 290.5 967.3 502.1 217.2 701.2 501.4 343.1 246.8 1293.5 255.9 1190.9 503.6 1196.7 41.1 300.7 1124.3 62.1 102.7 766.2 129.1 906 245.5 309.6 265.8 760 952.2 556.1 1010.2 621.6 784.5 889.5 207.7 1277.3 191 1060.2 212.9 158.1 1224.8 643.6 983.2 942.1 790 93.4 518.4 1329.8 880.8 912.9 513.6 1051.7 961.5 891.8 939.7 1269.6 1256.8 933.3 658.1 1296.1 1283.7 1081.2 297 1131.1 323.4 490.4 1087.7 923.7 964.6 1200.5 26.6 114.6 430.7 1218.4 546.7 188.6 61.8 924 144.5 1149.4 311.1 964.5 15.8 943.5 1151.8 1075.8 610.1 431.3 513.5 1220 293.1 494.7 337.8 992.7 1053.6 530.3 432.2 596 610.7 279.6 129.5 955.5 518.3 276.4 929.7 140.9 1151.9 875.9 796.9 1334.5 696.6 610.5 847.9 1255 1010.6 731 1022.3 996.4 543.9 1056.9 1216.5 411.4 1206.3 324.5 831.7 940.2 1309.1 195.3 521.4 65.2 1009.1 507.3 627.8 1223.4 442.5 228.4 497 293.1 1156.7 345.4 609.4 589.9 1048.7 198.5 636.1 601.9 919.9 1032.5 1336 431.3 1057 1015.3 66.9 347.4 1247 1092.3 333.9 107 817.5 630.9 561 635.2 494.4 401.1 1321.7 647.6 504.3 26.4 471.3 163.5 823.2 1080.7 1124.8 316.2 381.9 947.9 326.4 1009.7 308.3 954.3 970.2 952.2 949.2 1213.1 331.6 320.6 891.1 931.4 195 728.6 1199.2 614.9 1247.2 640.3 1304.2 645.4 530.7 295.6 962.9 179.7 625.4 555.3 166.4 274.6 939.2 949.6 982.3 777.3 921.6 1183.2 715.6 1023.1

Table 5.11: Samples of chromosomes with fitness values from CS2i3.

5.4 Key observations

The patterns of Pareto-frontiers in Figure 5.12–Figure 5.15 differ from each other, that allows to conclude that each industrial simulation model is a single optimisation problem. NSGA-II was used for the optimisation of the production plans and schedules. It would be interesting however to test the case basis of various genetic algorithms prior to the production use of the optimisation system.

Case studies 1 and 3 converged within 10'000 evaluations, while case study 2 did not. In addition to this, convergence dynamics of case studies 1 and 3 in Figure 5.12–Figure 5.13 allows to conclude that the initial set of parameters of these optimisation experiments is a good place to start experiments with other simulation models.

The plots in Figure 5.15 allows to test the idea of this research – optimisation of production plans and schedules using two-dimensional chromosome. Case study 1 clearly shows that optimisation of production plans and schedules provide better results than the optimisation of production schedules. A similar behaviour is presented in case study 3. In the case study 2, there are no clear dominance presented.

Iteration 4 experiments of case study 2 show that the optimisations have not been completed, see Figures 5.12 & 5.13. The author assumes that this has happened due to the size of chromosomes and complexity of the mode. There is a chance that a significant increase of the number of evaluations and size of population would allow to produce optimised results. This assumption is supported by plots CS2i4 1.5 and CS2i4 2 in Figure 5.14, where CS2i4 1.5 with smaller chromosomes show the progress of the optimisation while CS2i4 2 shows no optimisation.

Iteration No 4 dominates over Iteration No 3 in two cases out of three, which means that the unique behaviour of simulation models affects the optimisation results. If products or product groups in the database have similar production importance, and if Iteration No 4 dominates over Iteration No 3 on a particular simulation model, then Iteration No 4 is recommended for the optimisation of production plans and production schedules.

There is a minor difference between Iteration No 4 *1.5 and Iteration No 4 *2 in two cases out of three. One case suggests a dominance of Iteration No 4 *1.5 over

Iteration *2. This suggests that a number of products in the database during Iteration 4 sometimes makes a difference, and the optimum chromosome length has to be defined prior to using this system as a planning tool.

A minimum of five optimisation runs with different seeds are required for each planning tasks. With an estimated time of 12 hours for one optimization experiment, it would take 2.5 days to run a set. As planning teams are working with periods of 1 - 8 weeks, it is feasible to use this optimisation system on real-time basis. Computers that are more powerful will significantly reduce the simulation time. One simulation model out of the four is too detailed to be used as a GA fitness function; however, Moor's law suggests that in few years time this criterion would not be important. With Iteration No 3 optimisation, more powerful computers would allow a comparison of results from different product mixes.

5.5 Summary

Tata Steel Europe, a large steel manufacturing company, faces a number of challenges in production planning and scheduling, namely; change of marketing trend from a small number of large volume orders to a big number of small volume orders is one of them. Another one includes lack of communication between sales, production, and planning departments. It was also mentioned that the current production planning and scheduling practices are biased, not to mention the lack of confidence of the planners in the optimality of their production plans. Developing a solution becomes more complicated considering the size and long life cycle of the production equipment – it is difficult and expensive to reallocate. These challenges were identified during the study of production planning and scheduling practices in Tata Steel Europe. The study was performed by using participant observations and unstructured interviews.

The literature was reviewed to familiarise the author with the concepts related to production planning in general and DES & GA. It was identified that there are five ways to improve the performance of the production systems using DES & GA, namely. 1) optimisation of time-sequenced introduction of products into production system (production schedules), 2) optimisation of dispatching rules within the production system, 3) optimisation of production parameters, machine of conveyor processing speed or buffer size may be named as examples, 4) optimisation of production site's layout, and 5) a composite solution of two or more above-mentioned approaches.

The first, time-sequenced introduction of products was selected for this research. However, the applications from the literature were focused on the optimisation of production schedules. The author hypothesised that time-sequenced introduction of products, with certain modifications, may be used for the simultaneous optimisation of both production plans and production schedules. The original version of time-sequenced introduction of products contains the times each product is introduced into a production system. The modified version extended the original version with an additional dimension to the list of products. This additional dimension is filled with '1' and '0', all the products marked with '1' form a production plan, while 0-marked products are out of a production plan. The original dimension contains the times for each product.

This modified chromosome was tested on three case studies. Each case study is the DES model of a production area in Tata Steel Europe. Three sets of experiments were performed. The first set was reserved to the original optimisation of production schedules. The second and third sets were reserved to the modified optimisation of simultaneous optimisation of both production plans and schedules. The difference between these two sets is in the number of products that were sent to be optimised; in the second set, the number was equal to 1.5 of the original to this case study and in the third – to 2 of the original.

The results of the experiments were discussed. The patterns of Pareto-frontiers differ from case to case, which means that each simulation model represents a separate scheduling problem; therefore, meta-heuristic optimisation algorithms must be used with DES models. Iteration No 4 dominates over Iteration No 3 in two cases out of three, which means real-life application of this optimisation must be tested for both options. There is a minor difference between Iteration No 4 *1.5 and Iteration No 4 *2 in two cases out of three, while one case suggests dominance of Iteration No 4 *1.5 over Iteration *2, which means that real-life application must be tested with different sizes of product lots. More generic issues that are related to the use of DES & GA are discussed in Chapter 8.

All three cases showed non-cost optimisation. This is happening because the company uses standard costing and is unable to estimate accurate costs of products. The cost estimation technique described in the next chapter overcomes this cost limitation of the company. This cost estimation technique can be used in combination with the optimisation system. The author identifies two ways. Firstly, the outcome from the simulation model can be transformed into cost used as a fitness parameter. Secondly, production planning can use cost as yet another decision making criterion while selecting production plan and schedule. Both ways however are possible and require additional work.

Chapter 6

Cost estimation with DES

6.1 Introduction

Tata Steel Europe is a mass production company managed by standards, which define various aspects of production management, accounting, *etc.* This company uses standard costing for the estimation of production costs, *i.e.* the production cost of one production area is measured in a number of £ per one unit of throughput which is a tonne of steel. According to this system, the products that are processed within one production area have one average production cost. For example £100 per tonne on average for three projects, while the real costs are different: £60 for the first, £80 for the second, and £160 per tonne for the third project; this is illustrated in Figure 4.24. In addition, the current marketing trend shows further customisation of products for customers, from a small number of high volume orders few decades ago to a large number of low volume orders now; this change makes standard costing approach less feasible to use. As a result, this company faces difficulties in answering questions such as '*What is the real production cost?*' This chapter describes a cost estimation technique that overcomes this limitation.

6.2 Proposed classification of cost estimation techniques

6.2.1 Proposed classification

One of the best examples of classifications is the periodic table of the chemical elements. This table not only groups chemical elements by chemical properties, but also provides the gaps for yet undiscovered chemical elements. The concept underpinning this classification is taken as the basis for the development of a new classification of cost estimation techniques, which could be capable of guiding a systematic research in the area of cost estimation, *i.e.* the development of new cost estimation techniques.

A number of techniques in the previous section have common features. The similarity arises either from the information used by the techniques, or from the methods applied to process this information. The same information could be utilised in the different methods, as presented in the papers of Cavaliery *et al.* [101], Zhang *et al.* [164], Shtub & Zimerman [165] and many others. Likewise, the same information processing methods could be used in different cost estimation techniques, with operation-based and detailed, parametric and tolerance-based techniques as examples.

In a simple form, a cost estimation technique is a combination of i) cost information; and ii) a method to process this information. Types of information and methods could be visualised in the rectangular axes of a two-dimensional diagram. A cost estimation technique is an intersection of elements from the axes, as shown in Figure 6.1. Some intersections (cost estimation techniques), as with the periodic table of chemical elements, may not have been considered by the research community yet; however, they still may hold relevance for both academia and industry. These intersections would indicate areas for further research. A diagram like this can be used as a systematic guideline for the development of new cost estimation techniques or for further research into existing ones. A concept of the scope of a cost estimation technique gives a bigger diversity in this area of research. Types of information, methods and scope are described in detail below.

A cost estimation technique uses analytic or parametric measures, as proposed by Curran [87] or information of either a product or process is not used (none). 'Analytic'

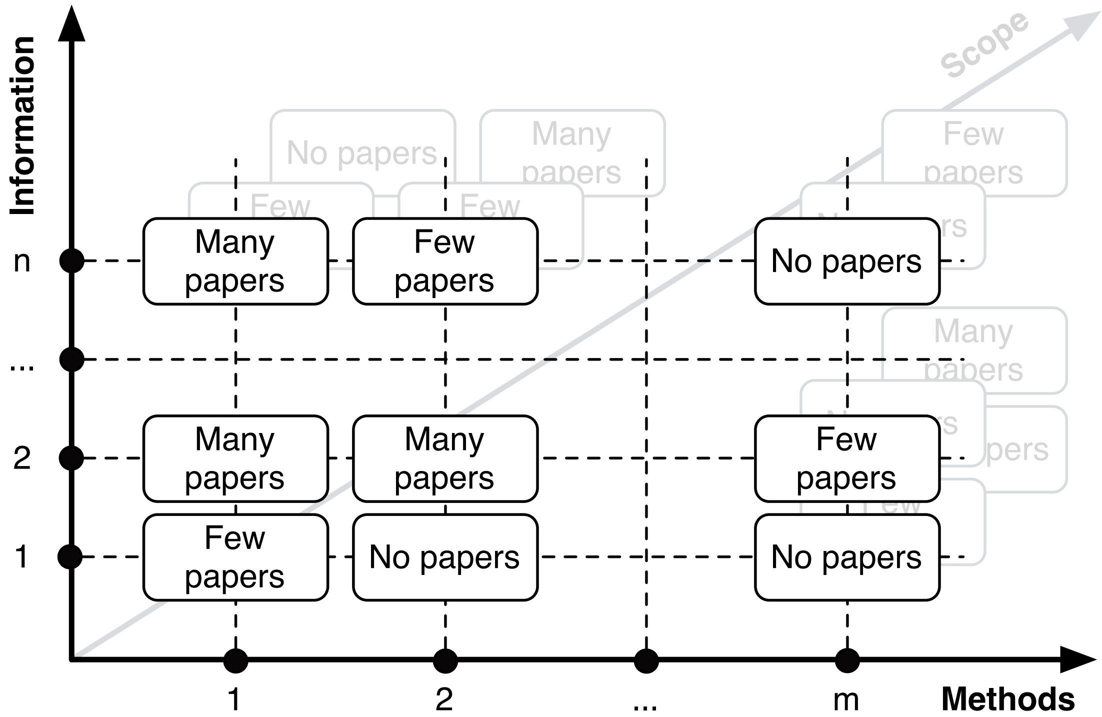


Figure 6.1: A cost estimation technique is a combination of information and methods to process this information. Cost estimation is limited by the scope of this technique.

means the structural characteristics of a product or process. 'Parametric' means the functional or general characteristics of a product or process. 'None' means there is very little or no information about a product or process. Examples are given in Table 6.1.

A number of information processing methods are used for cost estimation. Examples of those methods are arithmetic operations, artificial neural networks, Monte Carlo and discrete even simulation. The last two methods form a group of simulation based methods, while the rest form different groups. These groups of methods are named approaches in this research; the identified approaches are listed in Figure 6.2. This list is based on observed literature in the area of cost estimation. Obviously, this list is incomplete, and can be expanded with new approaches and methods, or even modified to provide better insights for systematic research in the area of cost estimation.

The scope of cost estimation techniques are based on PLC stages and the organisational specifics of the information utilised by a cost estimation technique. Activities in an organisation are value-added (get order, develop product, fulfil order, support prod-

Information about	Level of detalisation	
	Analytic	Parametric
Product	Components; features (step, cylinder, round, groove, stair, slot, depression, pocket, hole, clamp, bold, pin).	Number of parts or features; width, height, length, thickness, complexity, tolerance, material, diameter, size of casting, order quantity life time.
Process	Machine (lathe, mill, press); resource (labour, energy); transport (crane, transporter); operation (drilling, polishing, set-up time), assembly operations.	Process accuracy, run time, maintenance time, number of repairs, repair rate hour, number of products manufactured per hour, number of operations.

Table 6.1: Examples for different levels by depth of information of a product or process.

uct), management (set direction, formulate strategies, direct business) or support-related activities (manage finance, support personnel, manage technology, corporate learning). Trevor et al. [166] calls this classification of organisational activities by value matrix.

It should be noted that different stages of the product life cycle have different value-adding activities. A cost estimation technique is limited to at least one PLC stage and one area of organisational activities. However, cost estimation techniques can cover more than one area and PLC stage.

The research community provides a number of product life cycle models. These models have a lot in common; however, they also have some differences. A single PLC model does not have all of the PLC stages mentioned by the observed literature in cost estimation. The PLC model used in this paper is generated from the model used by Zheng *et al.* [167], Asiedu & Gu [168] and Jovane *et al.* [169]. The following PLC stages are used in this paper: conceptual design, detailed design, planning (production system design and planning), production (production and testing), realisation (distribution and realisation), service or use, and disposal.

In addition to the types of information and methods, there is another level of similarity regarding the ways in which cost information is processed by different methods. Overall, six ways, or, as referred to in this research, 'architectures' of cost estimation techniques were identified; these architectures are listed in Figure 6.3.

With *architecture I*, cost information is processed by one method within one phase of information processing. Two methods may be used separately *architecture II*, for the

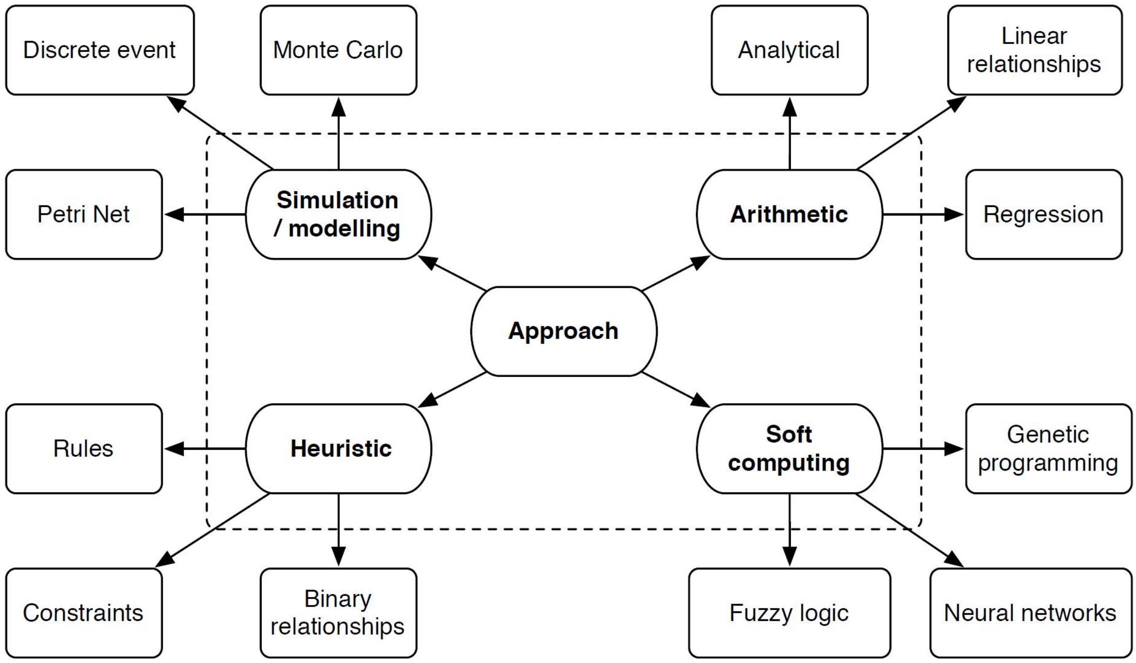


Figure 6.2: Approaches and methods used in cost estimation techniques.

purpose of estimating cost in different PLC stages or to gain confidence in the results of cost estimation. Each of these methods estimates cost within one phase of information processing. Cost estimation techniques of the *architecture III* are estimating cost within one phase; however, two or more methods are working together to estimate the cost of a cost object. *Architectures IV and V* look the same; however, within *architecture IV* the first method is **selecting** information for the second, and within *architecture V* the first method is **transforming** information for the second method. The *architecture VI* represents combinations of architectures from I to V.

6.2.2 Analysis using this classification

The observed literature is represented in Tables 6.2 – 6.5. Each of these tables contains references to papers on cost estimation techniques. Tables 6.2 – 6.4 represent *architecture I* with arithmetic, soft computing and simulation based approach respectively; *architectures II-VI* share Table 6.5.

A cost estimation technique is characterised by the types of cost information and scope of the technique. Each paper is referenced twice, in both parts of these tables.

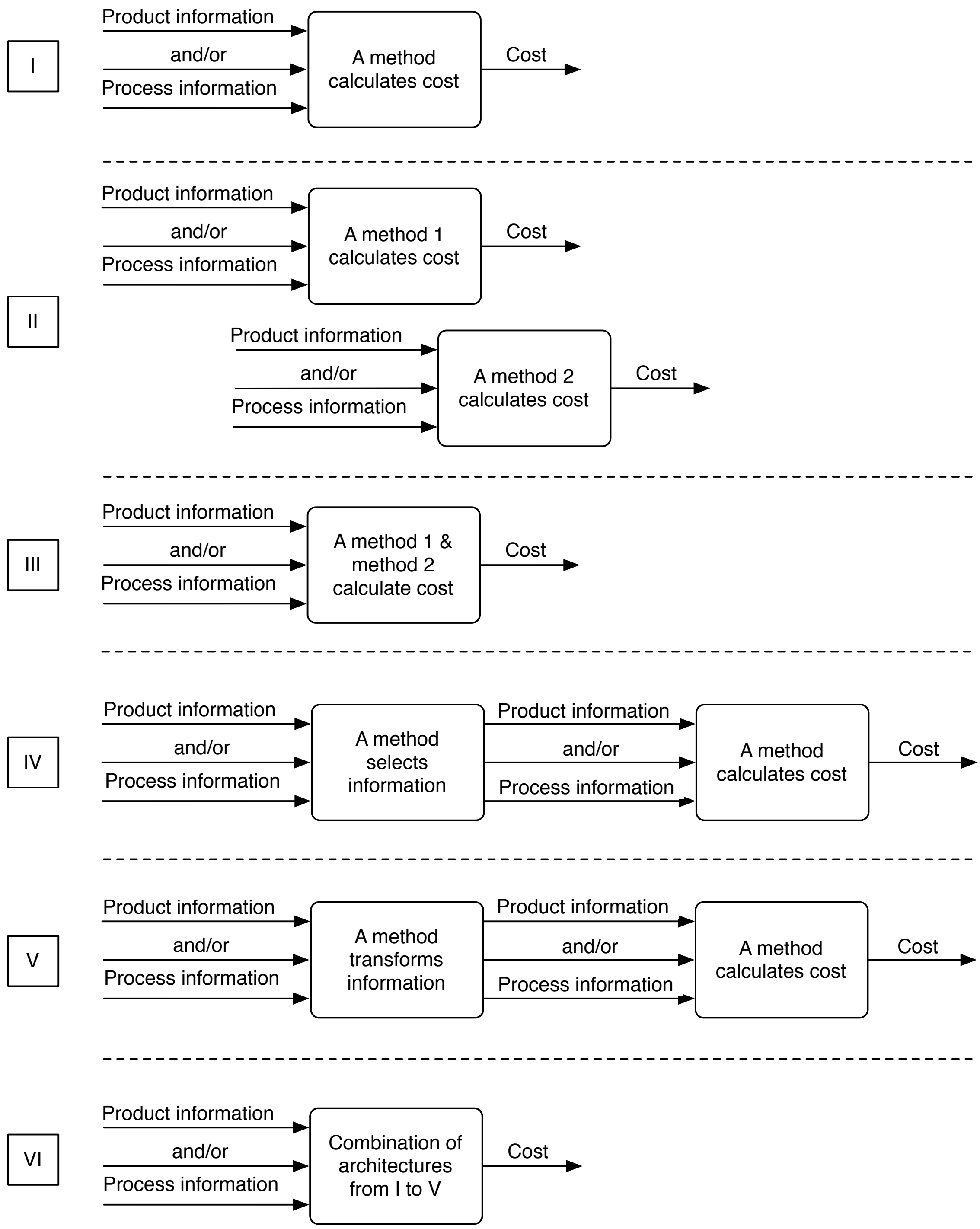


Figure 6.3: Architectures of cost estimation techniques.

Papers are grouped with square brackets; each group represents a commonly known cost estimation technique. The number of references from these tables have been summarised in Table 6.6.

A cost estimation technique is calculating cost **at** a PLC stage **for** a PLC stage, *e.g.* a function based cost estimation from Roy *et al.* research [47] is used **at** the conceptual design stage **for** cost estimation of the production stage. The references are listed in Table 6.7.

The grey cells in these tables mean that a cost estimation technique cannot be within these conditions. For example, a cost estimation cannot be without information as shown in Tables 6.2 – 6.6, while these cells in Table 6.7 show no reasons for cost estimation for these PLC stages, as next PLC stages in operation.

These tables may be used for analysis as follows. Firstly, the number of references in a cell show the relative measure of performed research for the combination of information and scope. Table 6.6 is the most suitable source for this analysis. For example, the cell of product-analytic and process-analytic information of the arithmetic approach has twelve papers cited, while the analytic-parametric combination of the same approach has one paper cited. This means, after a thorough literature review, the second cell has a bigger area of research in comparison to the first cell. Obviously, it is just one out of many possible explanations. For example, this single paper could answer the same number of research questions as twelve papers nearby, or it might not be as interesting for academia or industry.

Secondly, this analysis could be done in more detail, with methods instead of approaches. A cell with many references may have no methods, one or many methods. Some of these methods may never have been used for cost estimation before, which opens an opportunity for research. Thirdly, as references are mentioned in both parts of the table, a number of possible areas of research are growing rapidly, especially if we consider combinations of PLC stages in addition to the numbers of PLC stages a paper can cover. Tables such as Table 6.7 have to be used for this type of analysis.

Finally, a number of meta-questions can be raised. Examples of these questions are as follows: What is the best information and scope combination for a method? Why

Product		Process: Analytic	Process: Parametric	Process: None
Product	Analytic	A[170, 125, 171, 172, 123, 124], D[173, 174, 175], F[99], X[176, 177, 178]	R[164]	P[141, 179]
	Parametric	A[180], D[97], P[180], R[181], X[182, 183]	R[184], T[185], X[186]	P[101, 98], R[187, 188, 189, 190], T[103]
	None	D[193, 103], R[165]	P[194, 191, 192], X[195]	None

(a) Type of information

No of PLC stages		No of activity types: Three	No of activity types: Two	No of activity types: One
No of PLC stages	>Two	A[170], D[175]	D[173]	
	Two		A[124]	A[172], P[191, 192], R[190]
	One	A[171, 123], D[174, 97]	X[182, 183]	A[125], D[193, 103], F[99], P[141, 179, 101, 194, 98], R[187, 188, 181, 184, 189, 196, 164, 165], T[185, 103], X[195, 186, 176, 177, 178]

(b) Scope of the estimate

Table 6.2: Papers which describe cost estimation techniques with arithmetic methods of information processing, *architecture I*. Commonly known cost estimation techniques are represented with a letter as follows A - activity-based, D - detailed, F - feature-based, O - operation-based, P - parametric, R - regression-based, T - tolerance-based, X - name of the technique was not mentioned in the papers.

are the rest of the combinations not suitable for this method? Which architecture is the most suitable for a cell and why? Is there any correlation between information and scope?

		Process		
		Analytic	Parametric	None
Product	Analytic		[164]	[106]
	Parametric	[181]	[197, 105, 185]	[198, 141, 187, 188, 199, 101, 200, 189, 190]
	None	[165]		None

(a) Type of information

		No of activity types		
		Three	Two	One
No of PLC stages	>Two			
	Two			[190]
	One		[105]	[198, 141, 187, 188, 181, 197, 199, 101, 200, 185, 189, 106, 164, 165]

(b) Scope of the estimate

Table 6.3: Papers which describe cost estimation techniques with soft computing methods of information processing, *architecture I*. Only neural network cost estimation techniques have been found in the literature review.

		Process		
		Analytic	Parametric	None
Product	Analytic	D[123, 201], P[202, 203]		
	Parametric	D[151], K[204], M[205]		
	None	C[206]	M[207]	None

(a) Type of information

		No of activity types		
		Three	Two	One
No of PLC stages	>Two			K[204]
	Two			[205]
	One	D[123, 151, 201]		C[206], M[205, 207], P[202, 203]

(b) Scope of the estimate

Table 6.4: Papers which describe cost estimation techniques with simulation methods of information processing, *architecture I*. Simulation modelling methods are represented with a letter as follows D - discrete event simulation, C - Markov Chain, K - kernel, M - Monte Carlo, P - Petri Net.

		Process		
		Analytic	Parametric	None
Product	Analytic	II[208], IV[47, 209, 210, 211, 212, 213, 214, 215, 216, 217, 218, 17, 219, 93, 220, 221, 222, 95, 223, 100], V[224, 94], VI[225]	III[226]	III[227], VI[104]
	Parametric	IV[228, 229], VI[230]		V[231], VI[98]
	None			None

(a) Type of information

		No of activity types		
		Three	Two	One
No of PLC stages	>Two	IV[209]		II[208], III[227]
	Two	III[226], IV[222]		
	One	IV[218], V[94]	IV[229], V[231], VI[230]	IV[47, 228, 210, 211, 212, 213, 214, 215, 216, 217, 17, 219, 93, 220, 221, 95, 223, 100], V[224], VI[225, 104, 98]

(b) Scope of the estimate

Table 6.5: Papers which describe cost estimation techniques with *architectures II – VI*. Each architecture is represented with a number, which is mentioned in the name of the architecture from *II* to *VI*.

			Product									
			Analytic			Parametric			None			
			Process			Process			Process			
			Analytic	Parametric	None	Analytic	Parametric	None	Analytic	Parametric	None	Sum
Arithmetic I	Approaches	Arithmetic	13	1	2	6	3	7	3	4	None	38
		Soft computing	0	1	1	1	3	9	1	0	None	16
		Simulation	4	0	0	3	0	0	1	1	None	9
Architectures II–VI			24	1	2	3	0	2	0	0	None	32
		Sum	41	3	5	13	6	18	4	5		

Table 6.6: Number of references within each combination of the information types, approaches, and architectures.

		Cost estimation for the PLC stage						
		Development			Production	Realisation	Service/Use	Recycling
		Concept	Detailed	Planning				
Cost estimation at the PLC stage	Development – Concept	S[204]	S[204]	S[204]; III[227]	A[182, 179, 176, 190], N[198, 189, 190], S[204]; II[208], III[227], IV[47, 228, 214, 93, 220, 221, 95]	S[204]	A[190], N[190], S[204]	S[204]
	Development – Detailed		A[173, 170, 186, 124, 192, 177]	A[173, 124, 177]	A[173, 141, 188, 170, 181, 125, 186, 172, 124, 200, 97, 99, 185, 191, 184, 192, 177, 98, 178, 164], N[141, 188, 181, 199, 105, 185, 106, 164]; II[208], IV[209, 211, 210, 213, 214, 215, 17, 222, 223, 100], V[224, 231, 94], VI[225, 104, 98]	A[170]; II[208]	A[195], S[197, 207, 206]; II[208]	[208]
	Development – Planning			A[173, 124, 177]	A[173, 172, 101, 185, 177, 165], N[101, 185, 165], S[151]; III[226], IV[209, 212, 216, 217, 218, 219, 222]	III[226]		
	Production				A[193, 171, 172, 194, 123, 177, 196, 183], S[123, 202, 201, 203]; IV[209, 229], VI[230]		S[205]	
	Realisation							
	Service/Use							
	Recycling							

Table 6.7: The representation of cost estimation techniques used **at** a PLC stage to estimate cost of a product **for** a PLC stage. The groups of papers that are marked with letters represents the *architecture I* with A for arithmetic techniques, N for soft computing techniques, and S for simulation techniques. The rest of the groups represents architectures from *II* to *VI*.

6.3 High-level description of the technique

According to the classification of cost estimation techniques that is developed within this research project, (see Sections 6.2.1 and Table 6.4), simulation modelling (and DES modelling in particular) has been used by academia and industry for production cost estimation. The research suggests two different ways of using DES models for production cost estimation. Within this research, direct cost estimation means the use of DES modelling as a method of processing cost-related information with the costs as the output from these models, examples of this are provided in Table 6.4. The second way represents a novel cost estimation technique and is called a reversed cost estimation or product family based cost estimation technique.

This cost estimation technique extends the capabilities of production planning by providing another valuable characteristics of production plans and schedules to planners and managers.

A production system consists of machines that are processing various products. There could be many of these products - Tata Steel Europe Tubes have thousands of them that are different by shape, length, diameter, gauge, steel properties, and other various finishing options. Thousands of products are a hardly manageable amount unless categorisation is applied. This cost estimation technique utilises a concept from lean manufacturing – Product Family.

Products form a product family by sharing a unique combination of machines these products are going through. This categorisation depends on a concept used for categorisation and therefore, it can be 'generic' or 'detailed'. The granularity of categorisation depends on details and complexity of product families. For example, the concept of a machine (a particular function and location on the factory) may replace the concept of a group of machines sharing the same function yet having different locations in the factory. Or, the 'key' machines may be used for classification instead of all machines. If a company that applies this grouping wants to be more specific, it may apply the definition from the first sentence of this paragraph, and further differentiate product families by some product properties, i.e. shape, length or/and finishing operations. The author applied the simplest grouping as in the first sentence of this paragraph. Other

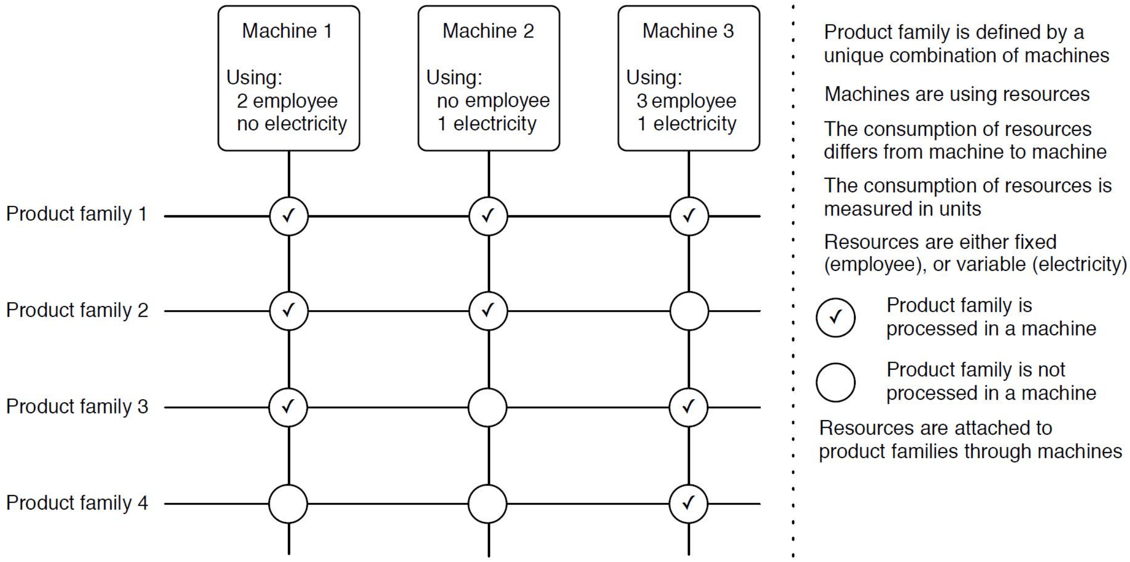


Figure 6.4: Product families.

factors may also be used for categorisation, for example, the selected way to categorise products does not include the sequence of products going through machines, which is a limitation of the selected categorisation.

Different machines use different combinations and consume different amounts of resources. This situation is shown in Figure 6.4. The cost that comes from resources and product families may not have the same cost as the standard costing system proposes them to have.

Information processing within this technique is divided into two phases. Utilisation and throughput values are calculated at the first phase, while the costs are estimated at the second phase. The overall architecture of the cost estimation technique is shown in Figure 6.5. According to the classification of cost estimation techniques, this technique has the fifth architecture of cost estimation techniques, (see Figure 6.3).

The function of the first phase is to calculate utilisation and throughput. This could be achieved by using DES, linear modelling, system dynamics, and other methods of simulation modelling. The author selected discrete event simulation because it is capable of accurate modelling of the dynamic and stochastic behaviour of a production system. Moreover, the visualisations of such models are widely used for model validation

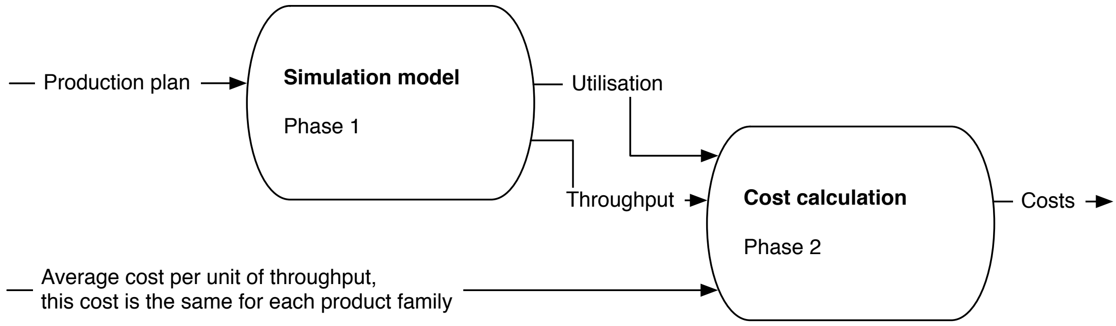


Figure 6.5: Overall architecture of the cost estimation system.

purposes; which provides certain credibility to the outputs of the models and therefore makes the results of cost estimation trustworthy.

The function of the second phase is to estimate costs for a unit of throughput of each product family. This model utilises the outputs from the first phase (utilisation and throughput) and average costs from standard costing system. The relationships between these concepts are visualised in Figure 6.6.

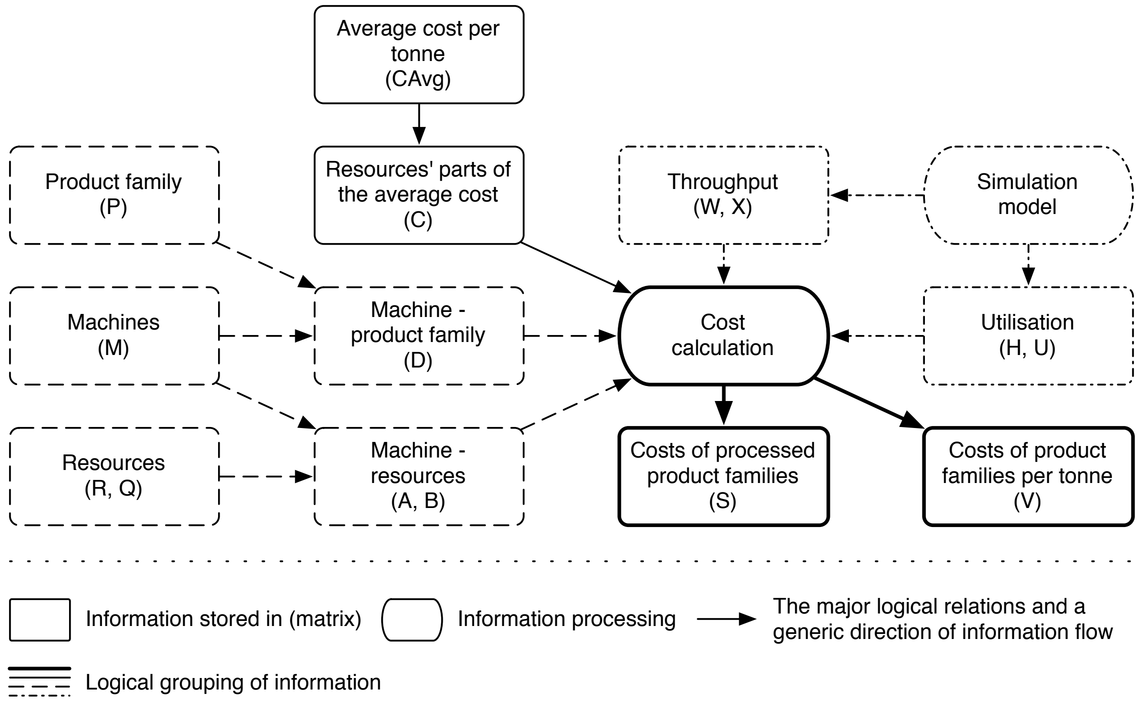


Figure 6.6: Concepts of the cost estimation technique.

6.4 Formalisation of the technique

A production system consists of a number of machines, from Machine m_1 to Machine m_{n_m}; these and other notations are given in Glossary. Each machine uses either one or many resources, different machines can use different resources, and the production system in total uses all resources, from Resource r_1 to Resource r_{n_r}. Formal machine-resource relationships are stored in matrix A_{n_r,n_m}, $a_{k_r,k_m} \in \{0, 1\}$, 1 if a resource is used in a machine. The consumptions of resources in machines are stored in matrix B_{n_r,n_m}, $b_{k_r,k_m} \in \{0, Q\}$.

$$A_{n_r,n_m} = \begin{pmatrix} a_{1,1} & a_{1,2} & \cdots & a_{1,n_m} \\ a_{2,1} & a_{2,2} & \cdots & a_{2,n_m} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n_r,1} & a_{n_r,2} & \cdots & a_{n_r,n_m} \end{pmatrix}; \; B_{n_r,n_m} = \begin{pmatrix} b_{1,1} & b_{1,2} & \cdots & b_{1,n_m} \\ b_{2,1} & b_{2,2} & \cdots & b_{2,n_m} \\ \vdots & \vdots & \ddots & \vdots \\ b_{n_r,1} & b_{n_r,2} & \cdots & b_{n_r,n_m} \end{pmatrix}$$

The production system is capable of processing a number of products. These products are grouped into product families, from Product Family p_1 to Product Family p_{n_p}. Product families are defined on the basis of machines applied to products, *i.e.* products processed in the same machines form a product family (sequence of processing is not covered within this model). Formal machine-product family relationships are stored in matrix D_{n_p,n_m}, $d_{i,l} \in \{0,1\}$, 1 if a product family is processed by a machine.

$$D_{n_p,n_m} = \begin{pmatrix} d_{1,1} & d_{1,2} & \cdots & d_{1,n_m} \\ d_{2,1} & d_{2,2} & \cdots & d_{2,n_m} \\ \vdots & \vdots & \ddots & \vdots \\ d_{n_p,1} & d_{n_p,2} & \cdots & d_{n_p,n_m} \end{pmatrix}$$

C_{Avg} is an average production cost from a standard costing system. The cost of a product is based on the cost of used resources, which means that the average production cost is the representative of the average costs of the utilised resources.

$$C_{Avg} = \sum_{k_r=1}^{n_r} C_{k_r} = \sum_{k_r=1}^{n_r} \beta_{k_r} \cdot C_{Avg} \tag{6.1}$$

, where β_{k_r} is a percentage of the average cost per tonne from a standard costing system, which is related to the average cost of a resource per tonne. Obviously, $\sum_{k_r=1}^{n_r} \beta_{k_r} = 1$.

The values of resource utilisations are stored in matrix $H_{n_r} = \begin{pmatrix} h_{n_1} & h_{n_2} & \cdots & h_{n_r} \end{pmatrix}$, these values are further used in Equation 6.2 to calculate the utilisation of a resource in a machine.

Some simulation modelling software have a built-in functionality to calculate utilisation for both resources and machines; in other cases, the calculation of the required utilisation takes an additional effort. A discrete event simulation package *Arena 11* was used in this research, as this package is the major simulation modelling software used in the company. *Arena 11* provides utilisation of machines and resources separately, therefore the utilisation of a resource in a machine is calculated using Equation 6.2. The outputs from these calculations can be validated using Equation 6.3. The values of the utilisation of resources in machines are stored in matrix U_{n_r,n_m}.

$$u_{k_r,k_m} = \frac{b_{k_r,k_m} \cdot h_{k_r}}{\sum_{i_m=1}^{n_m} b_{k_r,i_m}} \tag{6.2}$$

$$\sum_{k_m=1}^{n_m} u_{k_r,k_m} = h_{k_r} \tag{6.3}$$

$$U_{n_r,n_m} = \begin{pmatrix} u_{1,1} & u_{1,2} & \cdots & u_{1,n_m} \\ u_{2,1} & u_{2,2} & \cdots & u_{2,n_m} \\ \vdots & \vdots & \ddots & \vdots \\ u_{n_r,1} & u_{n_r,2} & \cdots & u_{n_r,n_m} \end{pmatrix}$$

Matrix $W_{n_p} = \begin{pmatrix} w_{n_1} & w_{n_2} & \cdots & w_{n_p} \end{pmatrix}$ stores throughput values for each product family. Matrix Y_{n_p,n_r} contains one part of utilisation of a resource per product family that comes from Equation 6.4, while Z_{n_p,n_r} being calculated with Equation 6.5 contains another part of utilisation of a resource per product family considering throughput of each product family.

$$Y_{n_p,n_r} = \begin{pmatrix} y_{1,1} & y_{1,2} & \cdots y_{1,n_r} & \\ y_{2,1} & y_{2,2} & \cdots y_{2,n_r} & \\ \vdots & \vdots & \ddots & \vdots \\ y_{n_p,1} & y_{n_p,2} & \cdots y_{n_p,n_r} & \end{pmatrix}; \; Z_{n_p,n_r} = \begin{pmatrix} z_{1,1} & z_{1,2} & \cdots z_{1,n_r} & \\ z_{2,1} & z_{2,2} & \cdots z_{2,n_r} & \\ \vdots & \vdots & \ddots & \vdots \\ z_{n_p,1} & z_{n_p,2} & \cdots z_{n_p,n_r} & \end{pmatrix}$$

S_{n_p,n_r}, S_{n_p} and V_{n_p,n_r} contain overall estimated relative costs and relative costs per tonne for each product family. These matrices are filled with outcome from Equations 6.6 and 6.8 respectively.

$$S_{n_p,n_r} = \begin{pmatrix} s_{1,1} & s_{1,2} & \cdots s_{1,n_r} & \\ s_{2,1} & s_{2,2} & \cdots s_{2,n_r} & \\ \vdots & \vdots & \ddots & \vdots \\ s_{n_p,1} & s_{n_p,2} & \cdots s_{n_p,n_r} & \end{pmatrix}; \; S_{n_p} = \begin{pmatrix} s_1 \\ s_2 \\ \vdots \\ s_{n_p} \end{pmatrix}; \; V_{n_p} = \begin{pmatrix} v_1 \\ v_2 \\ \vdots \\ v_{n_p} \end{pmatrix}$$

6.5 Linear model of the second phase

This model is capable of calculating two co-related costs: overall relative cost S and cost per tonne V of each product family. These costs are evaluated as follows.

Equation 6.5 evaluates part of the utilisation of a resource per product family and by considering throughput of each product family, these values are stored in Z_{n_p,n_r}.

$$y_{k_p,k_r} = \sum_{i_m=1}^{n_m} u_{i_m,k_r} \cdot b_{k_r,i_m} \cdot d_{k_p,k_m} \tag{6.4}$$

Equation 6.5 evaluates part of the utilisation of a resource per product family by considering throughput of each product family; these values are stored in Z_{n_p,n_r}.

$$z_{k_p,k_r} = \frac{w_{k_p} \cdot y_{k_p,k_r}}{\sum_{i_p=1}^{n_p} y_{i_p,k_r}} \tag{6.5}$$

Equation 6.6 evaluates values for S_{n_p,n_r}, this matrix stores the overall estimated costs.

$$s_{k_p,k_r} = \frac{z_{k_r} \cdot C_{k_r} \cdot \sum_{i_p=1}^{n_p} w_{i_p}}{\sum_{i_p=1}^{n_p} z_{i_p,k_r}} \tag{6.6}$$

Equation 6.7 evaluates values for S_{n_p}, this matrix stores the overall estimated costs of the processed product families.

$$s_{k_p} = \sum_{i_r=1}^{n_r} s_{k_p,i_r} \tag{6.7}$$

Equation 6.8 evaluates values for V_{n_p,n_r}, this matrix stores costs per tonne for each product family.

$$v_{k_p} = \frac{s_{k_p}}{w_{k_p}} \tag{6.8}$$

6.6 Validation

This section describes the validation of the concept – estimation of relative costs using utilisation and throughput.

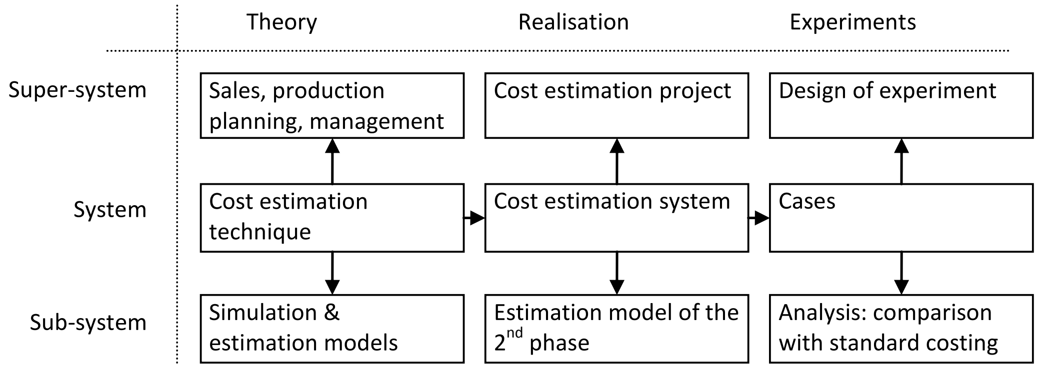


Figure 6.7: Elements of the systematic validation of the cost estimation's part of the research.

The author used the matrix for systematic validation of the research concept. This is a square matrix with three rows and three columns (see Figure 6.7). The row dimension covers a system view to a research concept – the cost estimation technique – and this view consists of a super-system, system, and sub-system levels of the research concept. The column dimension covers the theoretical, realisation, and experimentation parts of the research. Overall, if all nine elements within the matrix are valid, the research is valid as well.

The core research concept is the estimation of relative costs using two phases of information processing; utilisation and throughput are evaluated first, the estimation happens on the second phase. This core concept fills the system level of the theoretical part of the matrix. This cost estimation technique would provide costs to sales, production planning, management; therefore, these domains fill the super-system level of the theoretical part of the matrix. The technique (on the system's level of the research) consists of a simulation and cost estimation sub-models, each of these components has its own specifics; therefore, these components fill the sub-system level of a theoretical part of the matrix. The full matrix is shown in Figure 6.7.

Part	Level	Elements	Criteria	Method
Theory	Super-system	Sales, production planning, management	Does it add value to these domains? Does the technique contradict the system?	Logical reasoning
	System	Cost estimation technique	Could the combination of principles work?	Logical reasoning
	Sub-system	Simulation estimation models	Are these principles good for the production?	Logical reasoning, check measures
Realisation	Super-system	Cost estimation project	Valid development processes are used.	Logical reasoning
	System	Cost estimation system	The system estimates costs for a simple theoretical example	Experiment, Logical reasoning
	Sub-system	Estimation model of the 2nd phase	Standard costs are comparable with estimated costs.	Logical reasoning
Experiment	Super-system	Design of experiments	Rationality of argumentation of DES model's selection for case studies.	Logical reasoning
	System	Cases	Cases are industrial and relevant.	Case studies, logical reasoning
	Sub-system	Estimation model of the 2nd phase	Standard costs are comparable with estimated costs.	Logical reasoning

Table 6.8: Summary of the validation process.

The validation of development of super-system level is different from the validation of the components of the cost estimation system: different criteria are important for the study and different methods are used. A summary of the validated methods and related criteria and methods is provided in Table 6.8.

6.6.1 Theory

Super-system – theoretical level. This element of the research would be valid if the technique adds value to the end users, namely people from sales, production planning or manufacturing management. Each of these knowledge domains has different need for accurate cost estimation. The sales section is interested in profit maximisation, and accurate costs this technique would add to the price management. Production planning is interested in optimisation of production plans, including cost or profit, importance or throughput criteria, and accurate costs would add to some of the optimisation exercises. Manufacturing management, depending on the paradigm, is interested in maximum throughput (by the paradigm of Theory of Constraints) or waste reduction (lean manufacturing), or quick process reconfiguration (agile manufacturing) as described in Bititci et al. [154] paper, and accurate costs would add focus to the most important product families, the most important in terms of business value – profit. Currently, standard costing is used and while providing accurate costs, this cost estimation technique does not contradict to standard costing (averaged, these accurate costs are equal to standard costs); therefore, no major change in cost accounting procedures is required. This validates the research on the super-system – theoretical level.

System – theoretical level. This element of the validation matrix would be valid if the technique would have no contradictions between the technique's concepts. In general, a cost estimation technique is a method of information processing that uses some data for input and provides costs as output. This cost estimation technique uses i) throughput for each product family, ii) utilisation of machines and resources, and iii) average costs for a products within a production area. As described in Section 6.2.1, this covers both product and production dimensions of information; therefore, on a system level, the cost estimation technique could be capable of cost estimation. The accuracy of costs comes from the accurate values of utilisation and throughput, and DES models can deliver accurate utilisation and throughput values. This validates the research on the system – theoretical level.

Sub-system – theoretical level. This element of the validation matrix would be valid if the equations pass the check for measures. The technique as a system consists of two sub-systems. The first is the discrete event simulation model of a production system that takes a production plan as input. The output delivers accurate utilisation of machines and resources, as well as, the throughput per product family. As reviewed in Section 2.4, DES modelling is a well-known technique for accurate simulation modelling of production systems; therefore, DES modelling is valid for use in the first phase of the cost estimation technique. The second sub-model is a linear model that distributes standard costs between product families on the basis of utilisation of resources. As Equations from 6.4 to 6.8 have passed the check for measures (shown in Table 6.9) then this validates the research on the sub-system – theoretical level.

Equation No	Formula	Measures
6.4	$y_{k_p,k_r} = \sum_{i_m=1}^{n_m} u_{i_m,k_r} \cdot b_{k_r,i_m} \cdot d_{k_p,k_m}$	$[1] * [resource] * [1] = [resource]$
6.5	$z_{k_p,k_r} = \frac{w_{k_p} \cdot y_{k_p,k_r}}{\sum_{i_p=1}^{n_p} y_{i_p,k_r}}$	$\frac{[product]*[resource]}{[resource]} = [product]$
6.6	$s_{k_p,k_r} = \frac{z_{k_r} \cdot C_{k_r} \cdot \sum_{i_p=1}^{n_p} w_{i_p}}{\sum_{i_p=1}^{n_p} z_{i_p,k_r}}$	$\frac{[product]*\frac{cost}{[product]}*[product]}{[product]} = [cost]$
6.8	$v_{k_p} = \frac{s_{k_p}}{w_{k_p}}$	$\frac{[cost]}{[product]}$

Table 6.9: Check equations for units of measure.

6.6.2 Realisation

Super-system – realisation level. This element of the validation matrix would be valid if a valid development processes are used. Realisation of a cost estimation project comprises of two major parts: i) development of a simulation model of a production system, ii) adaptation of the cost estimation model of the 2nd phase for this simulation model. The first part is well described in Section 2.4.4, the author also contributed to this process as is described in Chapter 7; in general, this well-developed process, including validation of a simulation model, allows delivery of trustworthy values of utilisation and throughput. The second part, considering Sections 6.4 & 6.5, require accuracy through adaptation of a cost estimation linear model for a simulated manufacturing system. Therefore, as the technique has well-developed methodology for the realisation of a cost estimation project, this validates the research on the super-system – realisation level.

System – realisation level. This element of the validation matrix would be valid if the cost estimation would work on a simple theoretical example, because one could fully understand each aspect of a 'simple' example. Such model was described in Section 2.4.3, it was also used in validating the optimisation's sub-project, see Section 5.3.2. The following paragraphs relate the model to concepts of the cost estimation technique; use Section 6.5 as reference.

The following discrete event simulation model represents a simple theoretical production system. This production system consists of three machines, four product families and two resources, employee as a fixed resource and electricity as a variable resource. Information on this production system is given in matrices B^t, D^t, F^t below. The machines form a sequential production system, *i.e.* an entity of a product has to pass through Machine 2 in order to get processed in Machine 3. Each machine can process one entity at a time and has a buffer for another entity. It takes one hour to process one entity in a machine. If an entity does not have to be processed in a machine, then it skips the machine within the period of 10 seconds. $C^t_{Avg} = £100$ per tonne, $\beta^t_{k_1} = 0.75, \beta^t_{k_2} = 0.25$.

The model runs for 480 hours of simulation time which represents a quarter having 5 days week, 8 working hours a day. The batches of products are represented with entities, the weight of a batch is assigned using multiplication of 5 (tonnes) to normal distribution with a mean of 1 and standard deviation of 0.2. The entities are introduced using exponential distribution with mean of one hour. These values are the same for all experiments.

$$B^t = \begin{pmatrix} 2 & 0 & 3 \\ 0 & 1 & 1 \end{pmatrix};\ D^t = \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 0 & 1 \end{pmatrix};\ F^t = \begin{pmatrix} 1 & 0 \end{pmatrix}$$

Nine experiments were performed with this model. Inputs for these experiments vary in product mixes and a number of entities are introduced in the simulation model. Three product mixes for three different numbers of entities have been tested, nine experiments in total. For example, out of 150 entities, 40 percent become a product family 1, 25 percent of entities become both product family 2 and 3, and the rest 10 percent are related to product family 4; these numbers describe the experiment No 1.1. These and the rest of the inputs are given in Table 6.10.

By using inputs for the experiment No 1.1 (hereinafter '$t_{1.1}$') the simulation model provides the following values on the resource utilisation, employee has utilisation of 0.4201, and electricity, as a variable resource, has utilisation of 1, *i.e.* all electricity is used in production. The values of resource utilisation are stored in matrix $H^{t_{1.1}}$.

Experiment	Product family				Entities No
	PF1	PF2	PF3	PF4	
No 1.1	40%	25%	25%	10%	150
No 1.2	40%	25%	25%	10%	200
No 1.3	40%	25%	25%	10%	250
No 2.1	10%	40%	40%	10%	150
No 2.2	10%	40%	40%	10%	200
No 2.3	10%	40%	40%	10%	250
No 3.1	10%	25%	25%	40%	150
No 3.2	10%	25%	25%	40%	200
No 3.3	10%	25%	25%	40%	250

Table 6.10: The inputs for experiments of the simulation model, (see Figure 5.10).

Experiment	PF1	PF2	PF3	PF4
No 1.1	309.2	188.9	153.7	81.5
No 1.2	401.5	267.1	214.1	91.0
No 1.3	485.4	315.0	294.2	122.2
No 2.1	84.2	294.3	273.4	81.5
No 2.2	112.5	379.6	360.6	91.0
No 2.3	143.2	460.8	490.6	122.2
No 3.1	84.2	198.1	196.0	267.0
No 3.2	112.5	230.1	257.8	373.3
No 3.3	143.2	281.0	308.0	484.6

Table 6.11: Throughput per product family in tonnes, (see Figure 5.10).

These and other values, using Equation 6.2, are used to calculate *resource utilisation in machines* (matrix $U^{t_{1.1}}$).

$H^{t_{1.1}} = \begin{pmatrix} 0.4201 & 1 \end{pmatrix}$; $U^{t_{1.1}} = \begin{pmatrix} 0.1680 & 0 & 0.2521 \\ 0 & 0.5 & 0.5 \end{pmatrix}$

The simulation model also provides the accumulated weights of products (matrix $W^{t_{1.1}}$) and the accumulated weights have been processed by machines (matrix $X^{t_{1.1}}$). These values are related to the first experiment, for example the values given in $W^{t_{1.1}}$ can also be found in the first data row of Table 6.11.

$W^{t_{1.1}} = \begin{pmatrix} 309.2 & 188.9 & 153.7 & 81.5 \end{pmatrix}$

Parts of the utilisation of a resource per product family are evaluated with Equation 6.4 followed by evaluation of parts of the utilisation of a resource per product family by considering throughput of each product family with Equation 6.5.

$$Y^{t_{1.1}} = \begin{pmatrix} 1.092 & 1 \\ 0.336 & 0.5 \\ 1.092 & 0.5 \\ 0.756 & 0.5 \end{pmatrix}; Z^{t_{1.1}} = \begin{pmatrix} 103.07 & 123.68 \\ 19.37 & 37.78 \\ 51.23 & 30.74 \\ 18.81 & 16.30 \end{pmatrix}$$

Equation 6.6 has been used to evaluate values for matrix $S^{t_{1.1}}$ which contains *the overall relative costs for each product family*. These calculations are followed by using Equation 6.8 which provides *relative costs per product family* (matrix $V^{t_{1.1}}$, £ per one tonne in this case). Relative costs for all experiments are shown in Table 6.12.

$$S^{t_{1.1}} = \begin{pmatrix} 29449.03 & 10874.65 \\ 5535.80 & 3321.83 \\ 14638.79 & 2702.83 \\ 5373.88 & 1433.19 \end{pmatrix} = \begin{pmatrix} 40323.67 \\ 8857.63 \\ 17341.63 \\ 6807.07 \end{pmatrix}; V^{t_{1.1}} = \begin{pmatrix} 130.41 \\ 46.89 \\ 112.83 \\ 83.52 \end{pmatrix}$$

The estimation model of the second stage was prototyped in Microsoft Excel. This model fills matrices S and V with values. Nine experiments (see Table 6.10) resulted in nine outputs presented in Table 6.12. This second phase linear model takes data from the simulation model, which is thoroughly described in Section 2.4.3, Figure 5.10 with the related text, Figure 6.4 with the related text, and this Section 6.6.2.

As summarized in Table 6.8, the working MS Excel prototype, in combination with the simulation model, validates the research on the system – realisation level.

Sub-system – realisation level. This element of the validation matrix would be valid if the estimation results do not contradict each other and values from standard costing. $C_{Avg} \cdot \sum_{k_p=1}^{n_p} W_{k_p} = 73330$ should be equal to $\sum_{k_p=1}^{n_p} S_{k_p} = 73330$ and $\sum_{k_p=1}^{n_p} V_{k_p} \cdot W_{k_p} = 73329.144$. As these values are equal, this validates the research on the sub-system – realisation level.

6.6.3 Experiments

Super-system – experimentation level. This element of the validation matrix would be valid with an adequate set of experiments to test the research ideas. Table 6.13 contains metadata for the simulation modelling and other projects have been performed during this PhD study. The projects are described with the following criteria: name

to resource	PF	1.1	1.2	1.3	2.1	2.2	2.3	3.1	3.2	3.3
Employee	PF1	95.2	96.0	95.0	109.0	106.9	106.1	105.3	104.4	104.5
	PF2	29.3	29.5	29.2	33.5	32.9	32.6	32.4	32.1	32.2
	PF3	95.2	96.0	95.0	109.0	106.9	106.1	105.3	104.4	104.5
	PF4	65.9	66.5	65.7	75.5	74.0	73.4	72.9	72.3	72.4
Electricity	PF1	35.2	35.4	35.7	44.9	44.8	44.7	44.9	44.8	44.7
	PF2	17.6	17.7	17.9	22.4	22.4	22.4	22.4	22.4	22.4
	PF3	17.6	17.7	17.9	22.4	22.4	22.4	22.4	22.4	22.4
	PF4	17.6	17.7	17.9	22.4	22.4	22.4	22.4	22.4	22.4
Total	PF1	130.41	131.39	130.69	153.86	151.76	150.83	150.15	149.22	149.25
	PF2	46.89	47.24	47.09	55.97	55.31	55.01	54.82	54.53	54.53
	PF3	112.83	113.69	112.82	131.44	129.35	128.46	127.72	126.80	126.89
	PF4	83.52	84.16	83.61	97.90	96.44	95.82	95.32	94.68	94.73

Table 6.12: Relative costs of product families (PF) per tonne for nine experiments.

No	Name	No of machines	No of product families in a dataset	Resources	Method of simulation modelling
1	Information system of Engineering Steels, Section 4.2.1	Not available	Not available	Not available	None
2	Assessment of a new production area, Section 4.2.2.1	2 machines	3 product families	Employee	Linear model
3	Internal transportation system, Section 4.2.2.2	10 production areas	Not available	Tug, transportation unit	Linear model
4	A crucial production area, Section 4.2.2.3	2 production areas	Not available	Not available	Conceptual model
5	Tata Steel Europe Tubes Bay 4 simulation modelling, Section 4.2.3	8 machines	10 product families	Employee	DES
6	Internal transportation system, Section 4.2.4.1	8 production areas	Not available	Tug, transportation unit	DES
7	Packaging, Section 4.2.4.2	1 machine	Not available	Side-loader	DES
8	Heating End of Stocksbridge mill, Section 4.2.5	4 machines	1 product family	Not available	DES
9	Shotton simulation model, Section 4.2.6	4 production areas	Not available	Not available	DES

Table 6.13: Selection of projects for validation of the cost estimation technique.

as ID, No of machines, No of product families, No of resources, method of simulation modelling. The projects that are described in Section 4.2 are listed in Table 6.13.

A number of criteria are used for the selection of some of the projects in order to validate the cost estimation technique. Firstly, a model should contain a number of well identified machines, and on the basis of this criteria, the 1st, 3rd, 6th, 7th, and 9th project are out of scope. Secondly, a model should process a number of product families; therefore the 4th and 8th are out of the scope. Thirdly, the identified resources that are used by machines, the 2nd and 5th projects satisfy all these criteria; therefore, the 2nd and 5th projects are used for validating the technique. This analysis validates the research on super-system – experimentation level.

The simulation models, such as those described in the Sections 6.6.2 and 6.6.3, are validated before being used. The validation means that outputs of these models are trustworthy, which validates the outputs of this cost estimation technique.

6.6.3.1 Case study 1

System – experimentation level, part 1. This element of the validation matrix would be valid if the case study has an adequate DES model, and it is applied as described in Section 6.6.2. The second project from Table 6.13 is used as the first case study for validation of the cost estimation technique. This project is based on a study of a new production area in Tata Steel Europe Tubes that was performed during this research project. The linear simulation model of this production area was developed by the author and was validated by the production experts who agreed with the model parameters and simulation results. This project is described in Section 4.2.2.1.

According to the formal representation of the cost estimation technique, this project is described with the notation from Section 6.4, see Glossary.

$B^{c1} = \begin{pmatrix} 1 & 1 \end{pmatrix}$; $D^{c1} = \begin{pmatrix} 0 & 1 \\ 1 & 1 \\ 1 & 0 \end{pmatrix}$

The production plan for year 2007 is used as inputs to the Excel-based linear simulation model; 52 week-based planning periods. This simulation model provides utilisation of a resource – employee – in both of the machines. This utilisation is stored in matrix U^{c1}), data for the first week are presented in this section, while the data for the rest of the weeks can be found in Appendix B, the same for throughput per product family W^{c1_1}.

$U^{c1_1} = \begin{pmatrix} 0.238 & 0.379 \end{pmatrix}$; $W^{c1_1} = \begin{pmatrix} 325.00 & 140.25 & 140.25 \end{pmatrix}$

This input data is transformed into relative costs by using the Equations 6.4—6.8. Matrices Y, Z, S, and V contain data about the first week, data on the rest of the weeks are provided in Appendix B. There is one resource within this case; therefore, matrices have one column.

$Y^{c1_1} = \begin{pmatrix} 0.238 \\ 0.436 \\ 0.197 \end{pmatrix}$; $Z^{c1_1} = \begin{pmatrix} 88.85 \\ 70.13 \\ 31.79 \end{pmatrix}$; $S^{c1_1} = \begin{pmatrix} 28201.76 \\ 22259.84 \\ 10089.30 \end{pmatrix}$; $V^{c1_1} = \begin{pmatrix} 86.8 \\ 158.7 \\ 71.9 \end{pmatrix}$

Relative costs per tonne for each product family are shown in Table 6.14

$C_{Avg} \cdot \sum_{k_p=1}^{n_p} W_{k_p}$ should be and indeed are equal to $\sum_{k_p=1}^{n_p} S_{k_p}$ and $\sum_{k_p=1}^{n_p} V_{k_p} \cdot W_{k_p}$; therefore, this proves that there are no mistakes in the calculations with Case study 1.

Week	1	2	3	4	5	6	7	8	9	10
PF1	86.8	69.7	70.4	64.9	86.6	67.4	85.1	67.2	95.2	70.9
PF2	158.7	155.7	153.2	146.3	158.4	154.3	160.6	149.3	156.4	157.1
PF3	71.9	86.0	82.8	81.4	71.8	86.8	75.5	82.1	61.2	86.2

Week	11	12	13	14	15	16	17	18	19	20
PF1	81.7	65.5	90.1	67.3	101.9	71.7	63.1	75.7	63.1	63.1
PF2	162.0	147.1	158.2	153.2	138.6	153.8	145.6	155.2	145.6	146.3
PF3	80.4	81.6	68.0	85.8	36.7	82.1	82.6	79.5	82.6	83.3

Week	21	22	23	24	25	26	27	28	29	30
PF1	78.2	61.6	75.2	62.7	68.2	62.0	66.8	60.7	66.4	61.7
PF2	160.2	144.8	156.0	145.8	152.7	143.3	149.3	144.2	149.2	142.8
PF3	82.0	83.3	80.8	83.0	84.5	81.3	82.4	83.5	82.8	81.1

Week	31	32	33	34	35	36	37	38	39	40	41
PF1	100.0	100.0	61.2	72.9	73.6	62.0	67.4	65.0	73.8	61.5	72.4
PF2	0.0	0.0	143.9	154.5	155.5	143.0	151.6	146.8	154.5	144.4	155.3
PF3	0.0	0.0	82.7	81.6	81.8	81.0	84.2	81.8	80.8	82.9	82.9

Week	42	43	44	45	46	47	48	49	50	51	52
PF1	72.4	63.6	71.3	59.3	66.7	70.1	70.7	63.7	71.0	85.3	101.9
PF2	155.3	146.3	154.4	142.6	149.0	151.7	153.5	143.9	153.4	162.4	126.8
PF3	82.9	82.7	83.2	83.3	82.4	81.6	82.8	80.2	82.4	77.1	24.8

Table 6.14: Relative costs per tonne for each product family, 52 weeks of year 2007.

6.6.3.2 Case study 2

System – experimentation level, part 2. This element of the validation matrix would be valid if the case study has an adequate DES model, and it is applied as described in Section 6.6.2. This industrial case is described in Section 4.2.3, a production area of a big manufacturing company. A discrete event simulation model of this production area is used in the first phase of the cost estimation. This model was developed by the author and validated by production experts both during the conceptual modelling stage and while processing a historical production schedule.

This production area consists of eight machines responsible for different operations; these machines form a semi-sequential production process. The company suggested to select one resource, employee as worth using in this simulation model, other resources *i.e.* electricity, water, floor space or maintenance were considered irrelevant in this simulation modelling project. Each machine has its own processing times; in some of the machines, processing times are dependent on the characteristics of products. If an entity does not have to be processed in a machine, then it skips the machine within the period of 10 seconds.

Information on this production system is given in matrices B^{c2}, D^{c2} below. Due to data confidentiality issues, C^{c2}_{Avg} is equal to £ 100 per tonne, and labels are used instead of names of the product families, $\beta^{c2}_{k_1} = 1$.

$$B^{c2} = \begin{pmatrix} 2 & 1 & 1 & 1 & 1 & 1 & 1 & 3 \end{pmatrix};\ D^{c2} = \begin{pmatrix} 1 & 1 & 1 & 1 & 0 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 1 & 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ 1 & 1 & 1 & 0 & 0 & 0 & 1 & 1 \\ 1 & 1 & 1 & 0 & 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 & 0 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 1 & 1 & 0 & 1 & 0 & 0 & 1 & 1 \end{pmatrix}$$

Data for the busiest week of simulation was taken from a production schedule of year 2008 and this became the worst case scenario for this production area. Data from this week were used for validation of this model. This simulation model calculated the employee utilisation equal to 0.2497; this value is stored in matrix H^{c2}. This and other values were used to calculate (with Equation 6.2) the resource utilisation in the machines (matrix U^{c2}). $U^{c2} = \begin{pmatrix} 0.0454 & 0.0227 & 0.0227 & 0.0227 & 0.0227 & 0.0227 & 0.0227 & 0.0681 \end{pmatrix}$

The simulation model also provided the accumulated weights of the products (matrix W^{c2}).

$$W^{c2} = \begin{pmatrix} 12.040 & 6.731 & 0.000 & 9.491 & 3.354 & 0.000 & 3.694 & 1.347 & 8.559 & 0.000 \end{pmatrix}$$

Equation 6.6 is used to evaluate the overall costs of product families, these values are shown in matrix S^{c2}. Product families' costs per tonne are evaluated with Equation 6.8 these values are shown in matrix V^{c2} below.

$$Y^{c2} = \begin{pmatrix} 0.3859 \\ 0.3178 \\ 0.3632 \\ 0.3632 \\ 0.3859 \\ 0.4313 \\ 0.3859 \\ 0.3178 \\ 0.3405 \\ 0.3632 \end{pmatrix}; Z^{c2} = \begin{pmatrix} 1.27 \\ 0.59 \\ 0.00 \\ 0.94 \\ 0.35 \\ 0.00 \\ 0.39 \\ 0.12 \\ 0.80 \\ 0.00 \end{pmatrix}; S^{c2} = \begin{pmatrix} 1289.28 \\ 593.53 \\ 0.00 \\ 956.54 \\ 359.13 \\ 0.00 \\ 395.56 \\ 118.79 \\ 808.70 \\ 0.00 \end{pmatrix}; V^{c2} = \begin{pmatrix} 107.08 \\ 88.19 \\ 0.00 \\ 100.78 \\ 107.08 \\ 0.00 \\ 107.08 \\ 88.19 \\ 94.48 \\ 0.00 \end{pmatrix}$$

$C_{Avg} \cdot \sum_{k_p=1}^{n_p} W_{k_p}$ should be and indeed are equal to $\sum_{k_p=1}^{n_p} S_{k_p}$ and $\sum_{k_p=1}^{n_p} V_{k_p} \cdot W_{k_p}$; therefore, this proves that there are no mistakes in calculations with Case study 2.

Sub-system – experimentation level. This element of the validation matrix would be valid if the results from the case studies pass the same check as in Section 6.6.2. The last paragraphs of Sections 6.6.3.1 & 6.6.3.2 (the previous paragraph for the latter case) validate the research on the sub-system – experimentation level.

6.7 Adding to production planning

An approach for production planning and scheduling using genetic algorithms and discrete event simulation is described in Chapter 5. It was used to optimise production plans and schedules by two criteria: overall production time and throughput, and it was tested on three case studies. Production costs haven't been used due to the lack of this information; therefore, in such cases production planners would be unable to use cost as a decision-making criterion. This section shows the use of the cost estimation technique in such cases.

Case study 2 from this chapter is used to show the use of the cost estimation technique for production planning. The simulation model used in this case study is

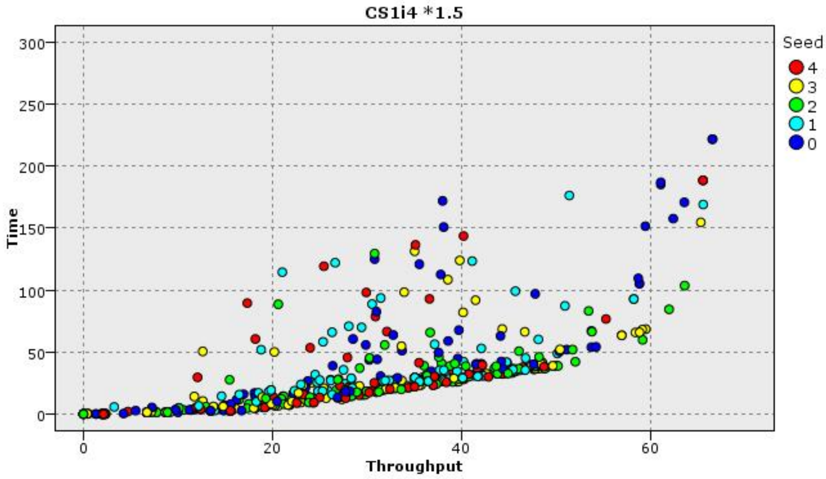


Figure 6.8: The last generations.

Plan No	Throughput	Time	Seed	ID	Employee utilisation
1	19.2	5	4	9977	0.0385
2	39.7	26	3	9929	0.1009
3	59.2	60	2	9919	0.1842
4	63.6	104	2	9959	0.2231
5	66.6	222	0	9918	0.2685

Table 6.15: Selected production plans for cost estimation.

similar to the model of Case study 1 from Chapter 5. As described in Section 5.4, Iteration 4 (a) data from this case study is better than Iteration 4 (b) and Iteration 3; therefore, this data is selected for the cost estimation.

A set of five Iteration 4 (a) experiments was run with different random seeds. The last generations from each run are plotted in Figure 6.8. Five production plans are selected from the Pareto-front, Table 6.15 shows the selected production plans, each of these plans also contains a part similar as shown in Table 5.6. This second part was used to estimate the utilisation and throughput per product family.

Table 6.16 contains the end result of cost estimation, this data can be further used by production planners or people from sales for decision making. The values are different because different product families and volumes result in different utilisation of resources per tonne for each product family.

Product family	Plan No				
	1	2	3	4	5
PF1	115.70	110.23	107.94	106.87	106.65
PF2	95.28	90.78	88.90	88.01	87.83
PF3	0.00	0.00	0.00	0.00	0.00
PF4	108.89	103.75	101.59	100.58	100.38
PF5	0.00	0.00	0.00	0.00	106.65
PF6	0.00	0.00	0.00	0.00	0.00
PF7	0.00	0.00	0.00	106.87	106.65
PF8	0.00	90.78	88.90	88.01	87.83
PF9	0.00	97.26	95.24	94.29	94.11
PF10	0.00	0.00	0.00	0.00	0.00

Table 6.16: Average cost per tonne.

6.8 Key observations

This technique calculates relative costs only (for example, product family 1 is more expensive in relation to product family 2). The proportions between costs of different product families and machines are as accurate as the values of utilisation and throughput that are calculated during the first stage. The simulation models, such as those described in the Sections 6.6.2 and 6.6.3, are usually validated before being used. The validation means that outputs of these models are trustworthy, which validates the outputs of this cost estimation technique.

The estimated values are based on the values of utilisation and throughput, and the cost from a standard costing system. The validity of the latter criterion cannot be checked with this cost estimation technique. The quality of the results depends on C_{Avg}, $\beta_{k_1}, \cdots, \beta_{k_r}$, and simulation models.

One theoretical and two industrial examples are described in this Chapter. Both of them show that this technique is capable of cost estimation in the situation, where traditional information for cost estimation is inaccessible, *i.e.* the cost of resources or parts or similar products.

The theoretical case and the first case study show a surprising difference in the estimated costs of product families. Table 6.17 contains cost values for product families

Case	Minimal cost	Maximal cost	Standard cost
Theoretical, see Section 6.6.2	52.38	144.17	100
Case 1, see Section 6.6.3.1	71.97	143.90	100
Case 2, see Section 6.6.3.2	88.19	107.80	100

Table 6.17: Average estimated costs per tonne.

with minimal and maximal averaged estimated costs. Considering these cases, it is possible to assume that the product families in other cases would also be different to the standard costs.

6.9 Summary

Tata Steel Europe is a large mass production company, which utilises standard costing system. It means that the factory is divided into smaller areas that accumulate both throughput values and costs during a production year, and afterwards the accumulated cost is divided by the throughput with the cost per tonne as the result. These values define the cost for all the products being processed within the production areas whether all the machines are being used or a part of them. Therefore, this system does not allow cost differentiation between products being processed within one area. A new cost estimation technique was developed as a solution for this problem.

A two-phase product family based cost estimation technique is described in this chapter. The first phase provides the values of utilisation and throughput for the second phase. This information, in combination with costs from standard costing system, is used to estimate relative costs per tonne for product families and machines. This makes possible a rationale decision making in production planning, sales and other domains with the requirement of knowing the cost diversification of different products.

A classification of production cost estimation techniques for systematic research in this area was developed. The proposed classification defines cost estimation techniques on the basis of cost information and methods used to process this information. Basic architectures of information processing, as well as stages of product life cycle; these cost estimation techniques are used and reviewed. The developed cost estimation technique fit into this classification having the fifth architecture and using relational method of information processing at the second stage.

Discrete event simulation modelling is one of the core concepts of Chapters 5 and 6 because DES models are capable of providing accurate results while simulating complex dynamic and stochastic production systems. One of the limitations of using DES modelling as an industrial tool is the high effort required to develop a DES model. The next chapter provides a solution for this issue.

Chapter 7

An information collection framework for simulation model development

7.1 Introduction

In Chapters 5 and 6 DES models are used for the optimisation of production plans and schedules, and cost estimation. The industrial use would require a significant number of DES models. The development of qualitative DES models is a time consuming process that requires DES modelling skills. The author proposes a technique of information collection for further development of DES models capable of cost estimation. This technique is designed for simulation engineers who are inexperienced in the field of simulation modelling to build qualitative simulation models that would support cost estimation.

Production engineers and managers are one of the major information sources about production systems. However, regardless of their production expertise, these specialists are usually inexperienced with the concepts and procedures of simulation modelling, which slows down and decreases the quality of simulation models.

Simulation modelling practice in Tata Steel Europe is summarised in the list below, and this list is similar to the one provided by Perera [145]:

- Simulation modelling is an iterative process guided by project objectives, these objectives are sometimes re-defined during the process of the project.

- Face-to-face meetings or 'workshops' are typical focal points for information collection.

- The transformation of notes collected into an electronic format requires basic skills, additional time and a disciplined organised approach.

- Information about some elements of a production system is more relevant than others and is re-assessed many times.

- Major information sources usually work at operation and middle level management. These people are experienced, yet lack knowledge of discrete event simulation. Their descriptions tend to be unstructured and case-based, thus, further interpretations by a simulation engineer are required.

- Due to personnel reallocation, simulation models tend to be forgotten, and it is difficult to reuse simulation models that have not been used for a few years.

- Besides, there are numerous technical issues concerning relevance, quality, and quantity of information as well as maintaining the storage and accessibility of information.

Many factors from the list are human-related. If the development of conceptual models would be intuitive to the people involved, mostly to production and simulation engineers who are inexperienced in simulation modelling, then it could reduce the impact of inexperience, incorrect problem definitions, lack of clear objectives, etc. Moreover, this information (without re-processing, stored in a special information system) would reduce a number of problems in the cases of the model's re-use.

This part of the research started with a request from the sponsoring company for a framework that supports the development of DES models. As in the other parts of this research, this request was validated with unstructured interviews, participant observations, and a literature review. Due to the specifics of the observation's results, complexity and variability of the DES modelling project, the early stages of a life cycle of DES modelling projects were selected as an area for academic research and industrial deliverables, namely, project definition, data collection, and conceptual modelling (hereafter conceptual modelling).

While de la Maza [232] developed a methodology of knowledge capture for further development of simulation models, the literature lacks specialised solutions for conceptual modelling of production systems, especially including costs of production systems. One of the major research methods of this research is the utilisation of knowledge from a normal scientific paradigm; this method is described in Section 3.6.1. The knowledge domains of cost estimation and manufacturing management were selected for the search and for further adaptation of the solutions.

Section 2.5 provides rationale for the selection of activity-based costing and value stream mapping for this research. These methods fit early stages of the DES modelling life cycle. These methods are well established and have been in the focus of academic and industrial communities for many years. These methods were utilised for the conceptual modelling, in the form of a process of information collection, for further development of discrete event simulation models of production systems that are capable of cost estimation. This process of information collection was prototyped in MS Access 2003.

7.2 Process of information collection

Two well established methods, *value stream mapping* and *activity-based costing*, were re-formed into the process of information collection. The basic information elements of value stream mapping [134] are customers, suppliers, processes, stores, and transporters. Activity-based costing [150] utilises the following basic information elements: resources and resource drivers, activities and activity drivers, products and orders. These two methods share some of the information elements. In a production system, an activity can be a *process*, *store* or *transport*. *Product* is used by both of the methods, while *resource* is used in activity-based costing. Most of these information elements are used in a typical discrete event simulation model; however, other informational elements, such as supplier or order, are usually not included.

These two methods differ in the process of information collection. Activity-based costing starts with the identification of the resources, followed by activities, assigning resources to activities, and finishes with assigning activities to products or orders. Value stream mapping starts with identification of processes, products, stores, and transporters, finishing with the development of the value stream map for this production system.

Activity-based costing is a process that incorporates most of the activities in an organisation and is used by managers and accountants; while value stream mapping can be used to model a part of a production system within an organisation, and is used by production managers and engineers. Because of the background of major information sources of DES modelling projects, and the nature of these projects, the process of information collection is taken from value stream mapping, and is extended with elements from activity-based costing.

Once the objectives of a DES modelling project are discussed and agreed with the main stakeholders, information collection and simulation model development projects may be divided into four stages. Information collection starts with definition of an overall information about a project (A1 in Figure 7.1), followed by actual information collection (A2 in Figure 7.1). The development of a generic simulation model goes third (A3 in Figure 7.1), and finishes with development of a detailed simulation model (A4 in Figure 7.1). It is an iterative process, the participants of a project could go through each stage a few times; however, most of the iterations usually happen in the stages of detailed simulation model (A4 in Figure 7.1) and information collection (A2 in Figure 7.1). The overall process of information collection and simulation model development is described with IDEF0 diagram in Figure 7.1, while the detailed list of activities is shown in Figure 7.4. IDEF0 diagrams were built according to the recommendations from IDEF0 method report [233] while using AI0 Win software.

At the first stage, a simulation project is defined by collecting information such as layout or history of this system (A11 in Figure 7.2), the objectives and scope of this project (A12, A13 in Figure 7.2), roles and contact details of the participants (A14 in Figure 7.2), as these details may be used both during this project and few months or even years later.

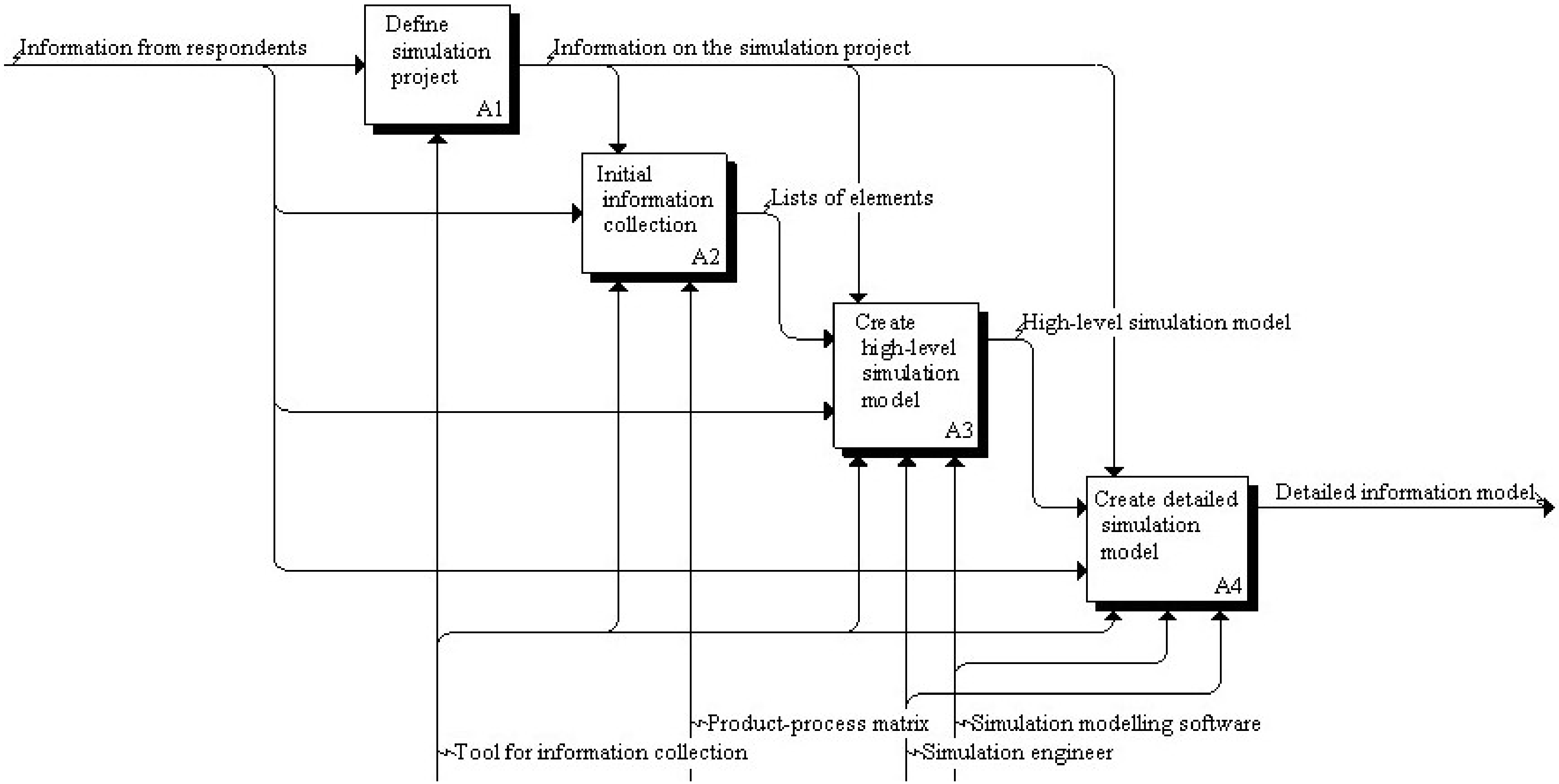


Figure 7.1: Overall process of information collection.

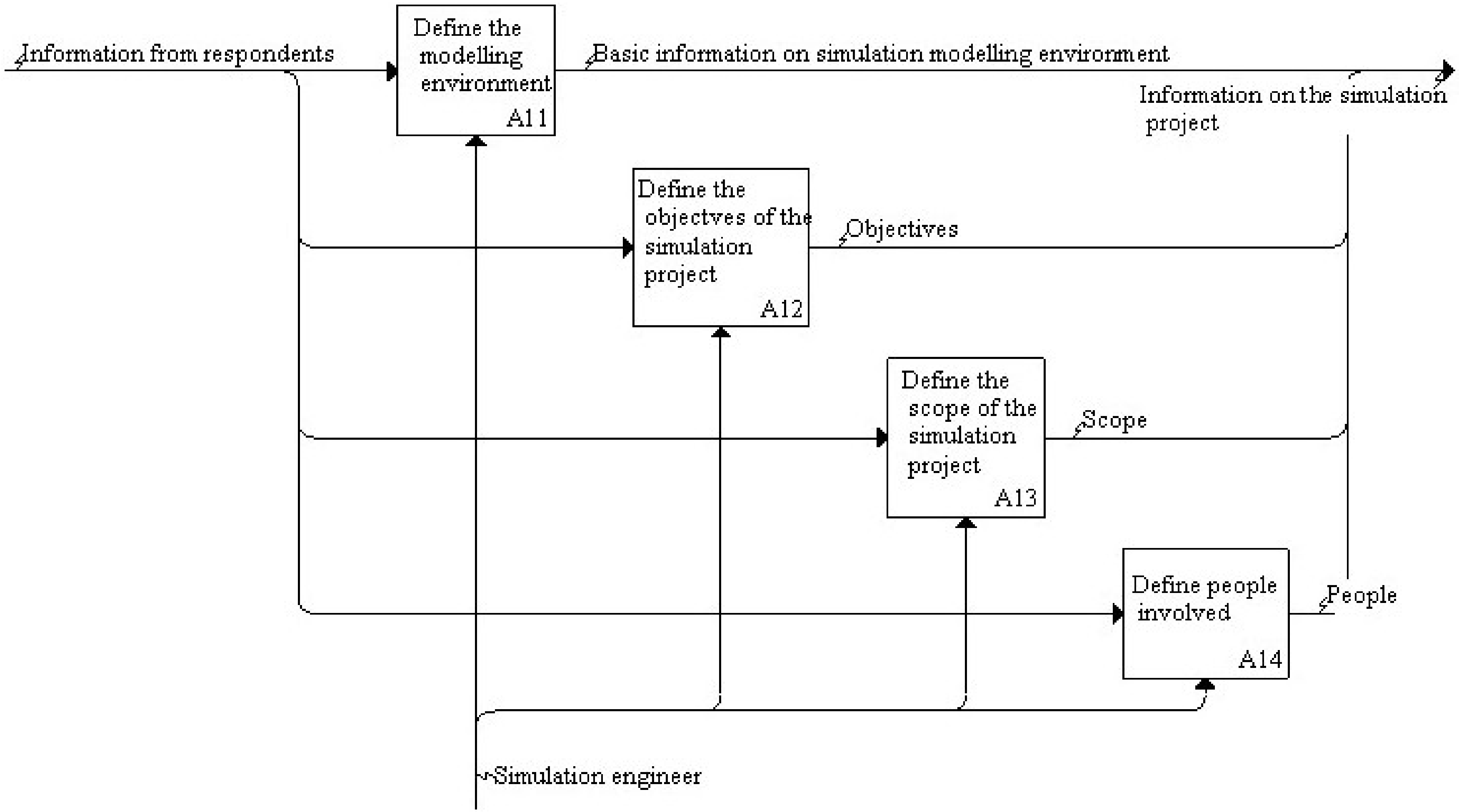


Figure 7.2: Defining a simulation project.

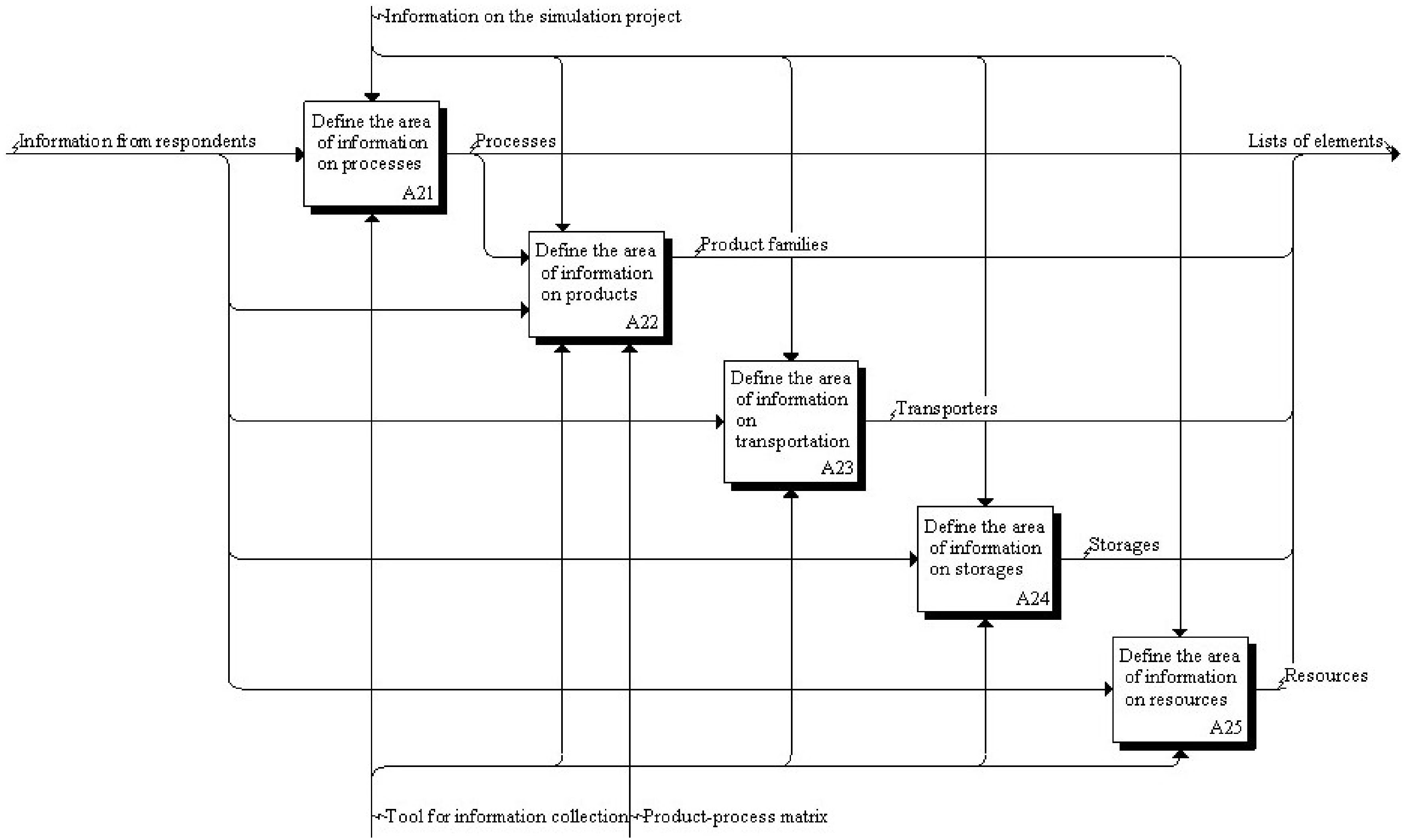


Figure 7.3: Defining elements of the production systems.

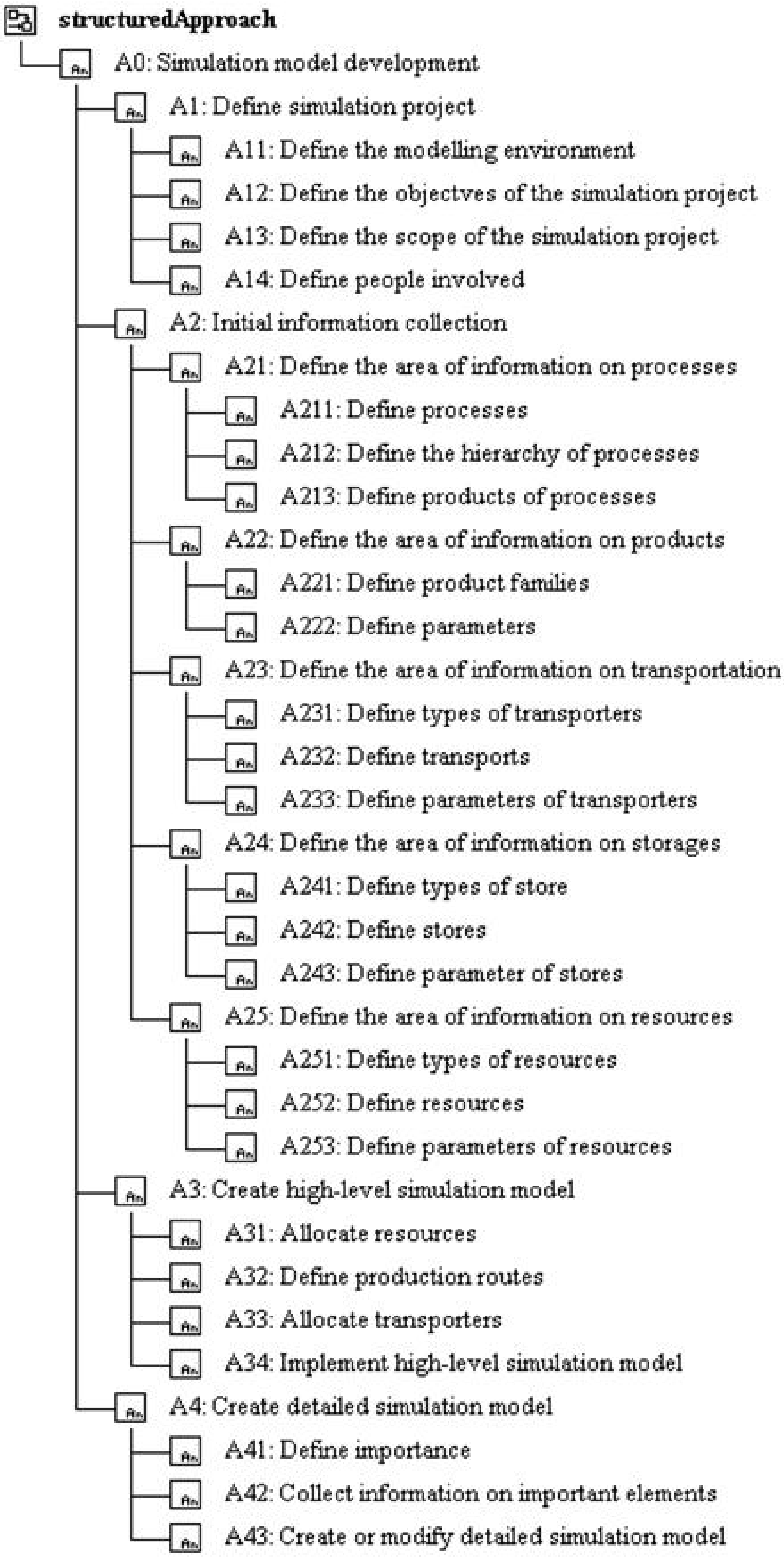


Figure 7.4: Overall process of information collection.

Elements	Generic model	Detailed model
Process	A process is modelled with a small number of elements with simple or no control logic.	A process is modelled with many elements having complex control logic.
Product	A product has few generic parameters, and is modelled with one entity through the process of simulation modelling.	A product has many parameters; these parameters are used in process routing and calculation of processing times. A product is modelled with many entities, which are batched and separated during the process of simulation modelling.
Store	A store is modelled with a time delay; entities wait to be pushed or pulled.	A store is modelled as a time delay. Parameters such as *time to store* are dependent on an entity and the parameters of its location.
Transport	A transport step is modelled with a time delay with dispatch based on a simple condition. Transporters have simple or no control logic.	A transport is a model of physical transport devices; route selection, or transportation time depends on parameters of entities.
Resource	Resources are not used or allocated without simple control logic. Resources have simple or no constraints.	Resources have complex control logic. Resources have a lot of constraints.

Table 7.1: Comparison of a generic and detailed simulation model.

At the second stage, information about the production system is collected: processes, products, stores, transporters, and resources. The first four of the mentioned information elements came from value stream mapping, while resources that introduce costs into an information model of a production system came from activity-based costing. The information collection process is illustrated in Figure 7.3. Each of these information elements utilise the same procedure of information collection, which starts with naming these elements and followed with defining parameters of these elements.

While information elements such as product, process, or resource are self-explanatory, the difference between generic and detailed models (stages A3 and A4) of the same production system is not that clear. Any of these models utilise most of the information elements; however this is on a different level of detail. The difference between generic and detailed simulation models is subjective and mostly relies on a set of unspoken rules within a small group of practitioners working together, i.e. a generic model of one group may be named as detailed by the members of the another one. The difference between these concepts within this document is summarised in Table 7.1. In reality, most models contain a mixture of generic and detailed elements.

During the third stage, connections between information elements are formed. At first, resources are allocating to processes (A31). This is followed by the definition of production routes by connecting processes, stores and transporters (A32, A34). These activities are listed in Figure 7.4.

Development of the detailed model happens at the final stage. It starts with the identification of elements' importance (A41), further information collection, and application of this information in a conceptual and simulation model (A42, A43). These activities are listed in Figure 7.4.

In the majority of cases, generic models are not enough to fulfil the objectives of projects. However, generic modelling is highly recommended for the following reasons: a) it is a convenient way to quickly understand a production system, b) it can identify information elements that require more detail, and c) it can emphasise the target issues within the company. Sometimes, a generic model is enough for identification of solutions, and the resources assigned to this DES modelling project may be used in other projects.

7.3 Validation

The author developed a matrix for systematic validation of a research concept. This is a three by three matrix, or a bi-dimensional matrix with three levels on each dimension. The first dimension covers a system view to a concept; and it consists of a super-system, system, and sub-system levels of a researched concept. The second dimension covers theoretical, realisation, and experimentation part of a research project. Overall, the systematic view consists of nine elements, and if all of them are valid, then the research is valid as well.

The core research concept is a process of information collection for further development of DES models capable of production cost estimation. This core concept fills the system level of a theoretical part of the matrix. This process is used for in the simulation modelling life cycle, therefore the life cycle fills the super-system level of a theoretical part of the matrix. The process focuses on collection production information; therefore,

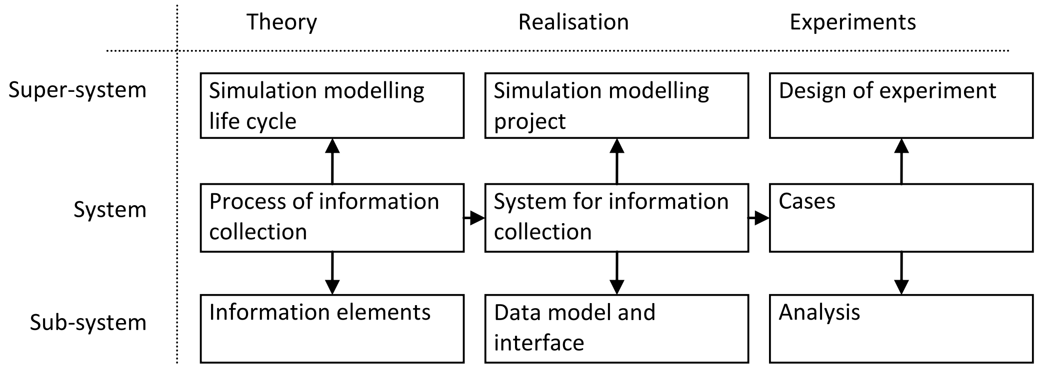


Figure 7.5: Elements of the systematic validation of the conceptual modelling.

information elements form the sub-system level of a theoretical part of the matrix. The matrix is shown in Figure 7.5.

Obviously, the validation of production planning and scheduling is different to the validation of the components in the optimisation system: different criteria are important for the study, and different methods are used. A summary of the validated methods and related criteria and methods is provided with Table 7.2. This information is further described in greater detail.

7.3.1 Theory

Super-system – theoretical level. This element of the research would be valid if the research concept fits the DES modelling life cycle. Section 2.4.4 provides an overview of the life cycle of DES modelling projects. Figure 2.7 shows the life cycle defined by Banks [108], conceptual modelling (in Banks it is divided into 'model conceptualisation' and 'data collection') is a part of it. The author proposes a process of information collection that is designed for further development of DES modelling capable of cost estimation; therefore, it fits DES modelling life cycle. Robinson [6] commented that conceptual modelling (also called information modelling) lacks research and later described a conceptual modelling for simulation [7, 8], and as the author has not found similar solutions in the literature, it fits the research. This validates the research on super-systems on the theoretical level.

Part	Level	Elements	Criteria	Methods of validation
Theory	Super-system	DES modelling life cycle	The proposed solution would fit within the life cycle.	Literature review, logical reasoning.
	System	Process of information collection	The proposed solution would work within the scope.	Literature review, logical reasoning.
	Sub-system	Sequence and elements that define the process.	The proposed solution would work within the scope.	Logical reasoning, literature review.
Realisation	Super-system	Process of database development	The process could be realised via databases. An adequate process of database development is used.	Logical reasoning
	System	Tool for information collection	The tool allows to store the data.	Testing.
	Sub-system	Data model and the interface	The tool allows to store the right data in the right sequence.	Logical reasoning
Experiment	Super-system	Design of experiments	A set of experiments may be used to test the research idea.	Logical reasoning
	System	Cases	Cases are industrial and relevant.	Observations, interviews, and logical reasoning
	Sub-system	Analysis of the hypothesis	The process is useful for case studies, experts agree with the process.	Logical reasoning

Table 7.2: Summary of the validation process.

System – theoretical level. This element of the validation matrix would be valid if the proposed solution would work within the scope. The information collection process is based on two well-established methods: *value stream mapping* and *activity-based costing* (see Section 2.5 for more information). The former is one of the tools of lean manufacturing, and it allows to model production systems, therefore is suitable for modelling of steel manufacturing processes. The latter is a well-known cost engineering technique that is used within a wide variety of industries, and therefore is suitable, in combination with *value stream mapping*, for the purpose of this research. This validates the research on the system – theoretical level.

Sub-system – theoretical level. This element of the validation matrix would be valid if the proposed solution would work within the scope. Figure 7.3, Table 7.1 and the related text, as well as Sections 2.5 provide information on the elements and sequences of information processing of *value stream mapping*, *activity-based costing*, and the proposed process of information collection. The latter starts as *value stream* *mapping* (therefore allows the right information to build an adequate DES model from that information) and finishes with defining resources; the source of costs in *activity-based costing* (therefore adds cost information to the model). This validates the research on the sub-system – theoretical level.

7.3.2 Realisation

Super-system – realisation level. This element of the validation matrix would be valid if an adequate methodology could be applied to develop the tool that would be further used to test the research concept. This tool is based on relational database technology, as the main purpose of this tool was to store and retrieve structured data, and the author has previous experience with relational databases. These reasons also applied to the selection of MS Access, this data model is shown in Figure 7.6 as the delivery tool.

The main purpose of the tool is to support the process, therefore the tool should collect the information elements in the designed sequence. A common approach to design a database would include the following activities: 1) data and reference material collection with further analysis, 2) development of conceptual and physical models 3) development of procedures and user interfaces, 4) development for integration and security issues, 5) testing.

1. This process was theoretically designed, it has no business documents (e.g. forms, correspondence); therefore, this stage was skipped.

2. The designed process already provides concepts with relationships between them; therefore, the database development was started with the design of a physical mode

3. As the process does not require automatic or semi-automatic data processing, there is no need for procedures for data processing. User interface is another issue; data would be easier to collect and retrieve with adequate user interfaces rather than the collection of data tables; however, no user experience and/or graphical designer effort is required for this prototype. An example of user interface of the tool is shown in Figure 7.7.

4. This is a standalone tool that would not contain any security information such as access rights; therefore, this activity can be skipped.

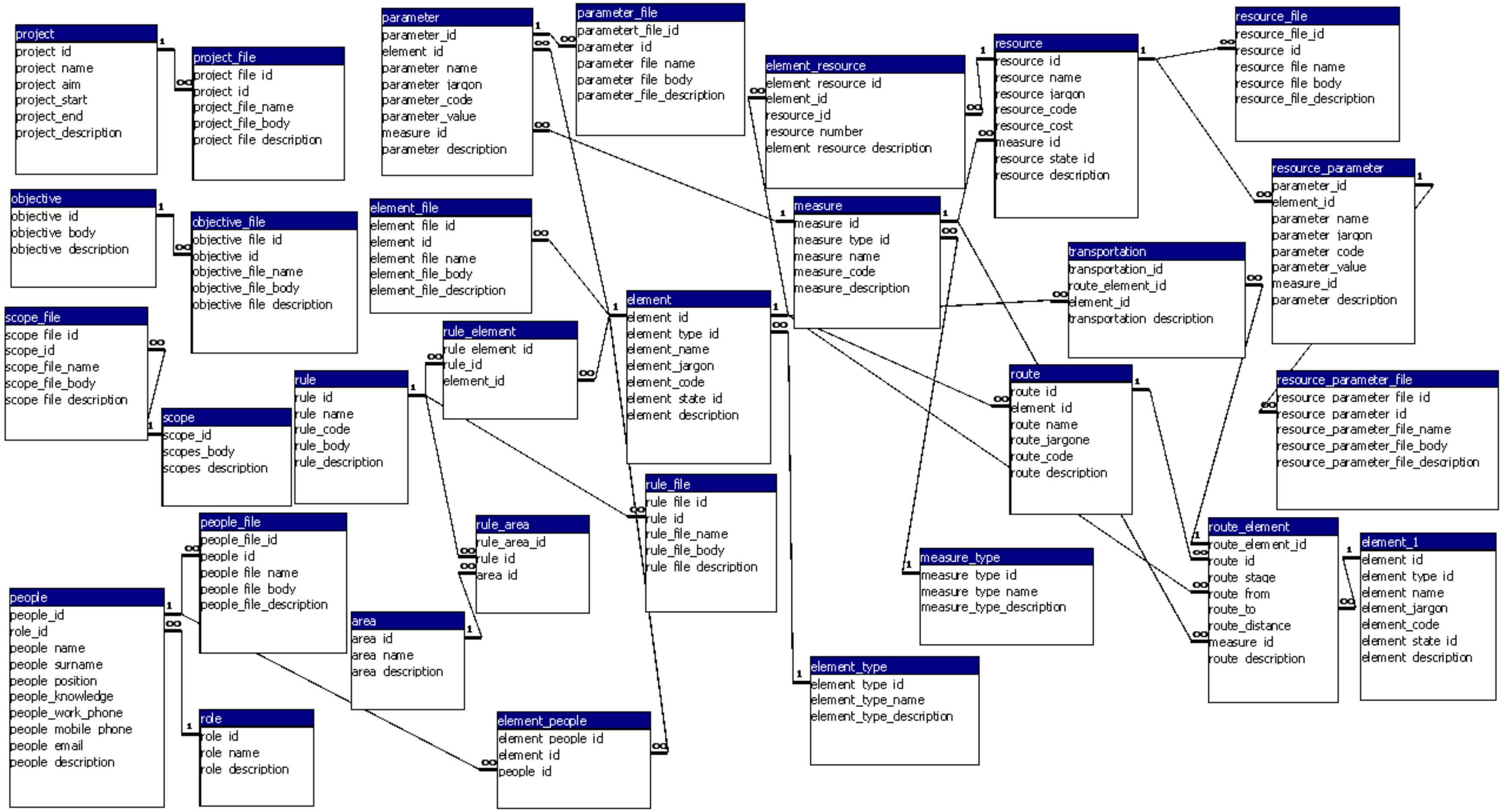


Figure 7.6: Physical model of the tool.

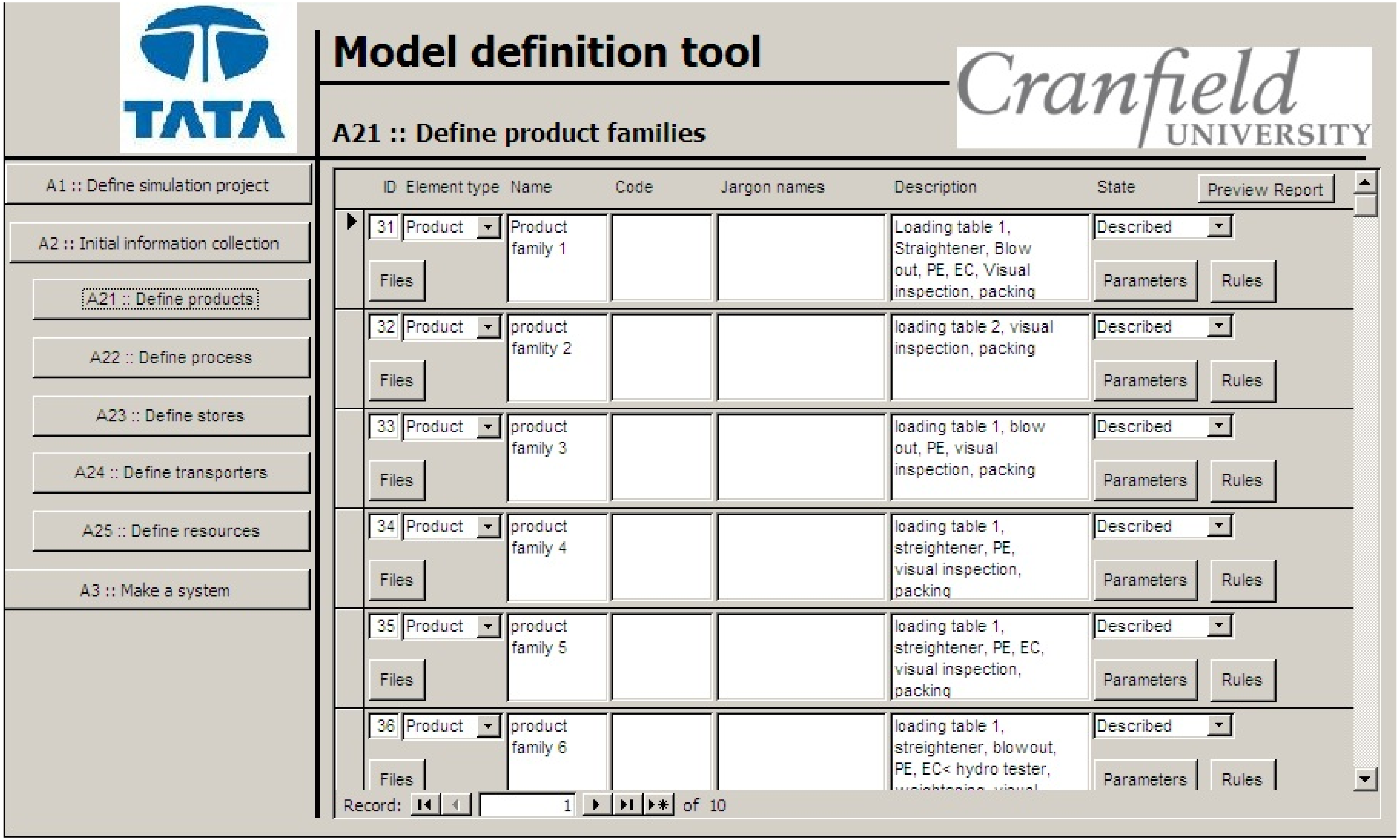
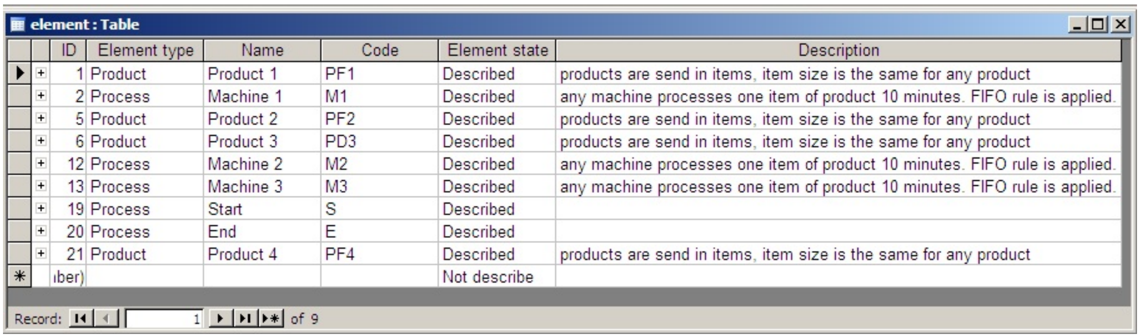


Figure 7.7: Example of user interface of the tool.



element : Table

ID	Element type	Name	Code	Element state	Description
1	Product	Product 1	PF1	Described	products are send in items, item size is the same for any product
2	Process	Machine 1	M1	Described	any machine processes one item of product 10 minutes. FIFO rule is applied.
5	Product	Product 2	PF2	Described	products are send in items, item size is the same for any product
6	Product	Product 3	PD3	Described	products are send in items, item size is the same for any product
12	Process	Machine 2	M2	Described	any machine processes one item of product 10 minutes. FIFO rule is applied.
13	Process	Machine 3	M3	Described	any machine processes one item of product 10 minutes. FIFO rule is applied.
19	Process	Start	S	Described	
20	Process	End	E	Described	
21	Product	Product 4	PF4	Described	products are send in items, item size is the same for any product
ıber)				Not describe	

Record: 1 of 9

Figure 7.8: Information sample of simple model stored in the database.

Therefore, with the main effort on the design of physical model and user interfaces in MS Access, this validates the research on the super-system, realisation level.

System – realisation level. This element of the validation matrix would be valid if the tool is capable of storing and retrieving data to a user. As has been expected from an off-the-shelf software such as MS Access, it delivers the required functionality (data storage and retrieval both through database tables and graphical forms). This validates the research on the system, realisation level.

Sub-system – realisation level. This element of the validation matrix would be valid if the tool collects information as defined by the information collection process. In order to test that, the author used the same simple theoretical model as used for testing in Chapters 6 and 7. This model is described in Section 2.4.3, Section 5.3.2 (see Figure 5.10 with the related text), and Section 6.6.2. At the end of the information collection process, the tool that contains information on all of the elements of the DES model with relationships between them that is required to build a DES model, therefore a conceptual model is complete. An information sample of a simple model stored in the database is shown in Figure 7.8. This validates the research on the system, realisation level.

7.3.3 Experiments

Super-system – experimentation level. This element of the validation matrix would be valid with an adequate set of experiments to test the research ides. Table 6.13 contains metadata for the simulation modelling and other projects have been studied during this

No	Name	Method of simulation modelling	Origin
1	Information system of Engineering Steels, Section 4.2.1	None	The author participated in the project from the start to finish.
2	Assessment of a new production area, Section 4.2.2.1	Linear model	The author participated in the project from the start to finish.
3	Internal transportation system, Section 4.2.2.2	Linear model	The author participated in the project from the start to finish.
4	A crucial production area, Section 4.2.2.3	Conceptual model	The author participated in the project from the start to finish.
5	Tata Steel Europe Tubes Bay 4 simulation modelling, Section 4.2.3	DES	The author participated in the project from the start to finish.
6	Internal transportation system, Section 4.2.4.1	DES	The author participated in the project from the start and reviewed the model at the end of this project.
7	Packaging, Section 4.2.4.2	DES	The author participated in the project from start and reviewed the model at the finish of the project.
8	Heating End of Stocksbridge mill, Section 4.2.5	DES	The author did not participate in the project from the start, though he reviewed the model at the end of the project.
9	Shotton simulation model, Section 4.2.6	DES	The author did not participate in the project from start, though he reviewed the model at the end of the project.

Table 7.3: Selection of projects for validation of the process of information collection.

PhD study. The projects are described with the following criteria: 1) project name as ID, 2) method of simulation modelling, and 3) the origin of the project. The projects that are described in Section 4.2 are listed in Table 7.3.

Some of the projects are selected for validation of the process of information collection. A number of criteria are used for this selection. Firstly, a project should include the development of DES model, and on the basis of this criteria, 1st, 2nd, 3rd, 4th project are out of scope. Secondly, the author should participate in the information collection stage, and should be able to compare the gathered information and the final DES model; therefore 8th and 9th are out of the scope. The 5th, 6th, and 7th projects satisfy both of these criteria; therefore, these projects are used as validation of the technique. This analysis validates the research on super-system, experimentation level.

System – experimentation level. This element of the validation matrix would be valid if case studies would prove applicability of the process. This process was tested on three case studies that represent various aspects of the production process. Firstly, processing of products by machines, secondly, transportation of products between production locations, ternary, packaging and storage of products. All these cases are described in the project's section of Chapter 4 (see Section 4.2), this section contains an overview of these cases.

In the first case study, the author played the role of a simulation engineer and collected information during one group meeting. Afterwards, this information was used to develop a generic simulation model; this model was modified and submitted to the company after the second meeting. In the next two cases, information was collected by MSc students working on simulation modelling projects of production systems; both of them had only a basic knowledge of discrete event simulation modelling. Afterwards these MSc students were asked to check the completeness of information, and the simulation models were reviewed. The feedback from MSc students confirmed that this tool and the process covered the essential information on the simulation models.

Case study 1. A simulation model represents one production area in Tata Steel Europe Tubes that is described in more detail in Section 4.2.3. This production area consists of eleven machines, excluding buffers, loading tables, and cranes. These machines form a semi-sequential production process with two-product entry and one exit point; parallel processing is not possible. External logistics is modelled with an entity generator, while internal logistics is represented with conveyors and a crane. Considering the number of basic information elements in this production system, and the implementation of relationships between these elements, this model may be stated as a medium depth simulation model of a medium size production area. Appendix C contains a series of screen-shots showing both the tool and collected information.

Case study 2. A simulation model represents the internal transportation system in Tata Steel Europe Tubes that is described in more detail in Section 4.2.4.1. The internal transportation system consists of a logistics coordinator that manages the movement of three tugs and thirty-four road transportation (RTS) units through a plant that is 1.5 x 1 km big. Considering the number and diversity of basic information elements in this production system, and the implementation of relationships between these elements, this model may be stated as a medium depth simulation model of a medium sizes transportation system.

Case study 3. A simulation model represents a packaging and dispatch area in Tata Steel Europe Tubes that is described in more detail in Section 4.2.4.2. Tata Steel Europe Tubes has a large storage area for orders waiting to be dispatched. The orders, tubes of different sizes, shapes, and properties are stored in either one or two tonne packs. These packs are stored in racks or bins, or on the floor, and are lifted with side lifters. Considering the number and diversity of basic information elements in this production system, and the implementation of relationships between these elements, this model may be stated as a medium depth simulation model of a medium sized storage area.

With the case studies that are industrial and relevant to testing of the process of information collection, this validates the research on system-experimentation level.

Sub-system – experimentation level. This element of the validation matrix would be valid if case studies could prove applicability of the process. The process is applicable if it allows the collection of the major information and is useful to the end user. This was validated with using this information collection process during three case studies. In addition, two industrial experts having more than ten years of DES modelling experience each reviewed the process and the tool, and their feedback is provided in the next paragraph.

Experts state that the unstructured nature of the workshop approach can be beneficial to the process, both in terms of engaging business personnel in the process, and in identifying the key project elements. Some modifications of the tool to accommodate this unstructured nature of information collection would be advantageous. Further discussions proposed the incorporation of multimedia components in the tool to capture and store video and audio descriptions as a potential enhancement. Overall, a valuable outcome would be to facilitate the flow of information from the unstructured thoughts of the typical highly experienced expert into the structured world of the simulation modeller. A tool which could support ongoing unsupervised updates of this information by the business experts would be ideal but the usability characteristics require development of Web 2.0 application. Overall, the methodology is sound, and provides a good framework to guide the simulation modeller in a structured way. The prototype tool developed supports this methodology well but needs further development to improve usability.

The outcome from the case studies and the results of experts' reviews validate the research on sub-system, experimentation level.

7.4 Summary

A number of research methods were utilised in this project starting from the 'standard' process of PhD research as described in Section 3.5.1. The research project started with a research objective from the sponsoring company; to develop a framework for DES models development in this case. This research objective was validated with informal interviews and participant observations, and with knowledge from the literature review. These problems are listed in Section 7.1 and highlighted with bold font in Table 2.11 and Table 2.12.

The objective was narrowed down to support the early stages of the DES modelling project: definition of a project, data collection, and conceptual modelling. These stages are selected because of their importance to quality and time aspects of DES modelling projects; improvement of the early stages would reduce time and increase the quality of projects; the later stages are also problem or application-specific, and therefore it is challenging to provide improvements to the procedure of DES modelling.

A process of information collection was used as a realisation of the conceptual modelling. A step-by-step process would guide simulation engineers, especially those lacking modelling experience and/or knowledge of production systems, in gathering information that is relevant to the case; simulation models of production systems and production cost estimation. Experienced simulation engineers may change the sequence of information collection, as this would not damage the natural flow of interviews; however, is recommended to inexperienced simulation engineers.

This process can be used as a guideline for simulation engineers, or a special tool for information collection may be utilised by the participants of a simulation modelling project. A prototype of such a tool was developed for the latter case; this tool was developed and used to validate the process.

The process was validated using three case studies that were taken in a form of participant observations, two interviews of the most experienced simulation engineers in Tata Steel Europe, and logical reasoning. The latter method of validation is described in Section 3.8. The former two methods are described in Sections 3.6.3, 3.6.4 and 3.6.5. These cases are described in Sections 4.2.3 and 4.2.4, the simulation model of the first case study (see Section 4.2.3) was also used in other parts of this project, optimisation of production plans and schedules, and cost estimation using DES models.

Chapter 8

Discussion and conclusions

8.1 Key observations in the company

The customisation trend is a result of progress in information, logistics, and management technologies (orders of customers may be controlled separately and processed in collaboration to each other). It also affected this steel manufacturing company, customers now order a large number of low volume orders instead of a small number of high volume orders few decades ago.

Steel manufacturing equipment is an example of massive engineering with long life cycle, it is expensive to buy, install, and re-allocate. The production systems in Tata Steel Europe – which were originally designed to satisfy the demand characterised by a small number of high volume orders – were unsystematically modified during the past decades, which complicates production planning and scheduling. With the current marketing trend to customisation, the production planning and operational management teams face regular challenges and operate on a fire-fighting basis.

Production business units share a management system as they are managed with standards, which define various aspects of production management, accounting, *etc*. This company uses standard cost approach for the estimation of production costs, *i.e.* production cost of one production area is measured in a number of GBP per one unit of throughput (a tonne). The market change also makes standard costing approach less feasible to use. As the result, this company faces difficulties in answering questions such as '*What is the real production cost?*', therefore, sales make contracts without awareness of accurate production costs, and capabilities of production systems.

Tata Steel Europe has expertise in DES, a computer simulation modelling technique, which is capable of accurate production cost estimation and, in combination with genetic algorithms, of optimal production planning and scheduling for complex production systems. A broad use of DES modelling for cost estimation and scheduling would require the development of DES models beforehand. Development of DES models is a time consuming process and the early stages of DES modelling life cycle sometimes take 50% of the projects' lead time. More DES models mean reduction of development time and/or more simulation engineers including production experts playing role of simulation engineers.

8.2 Discussion on the research methodology

The research methodology is described in Chapter 3 and this section is used for structuring the discussion. Therefore, strengths and weaknesses, rationale and alternatives are discussed for i) systems analysis, ii) research objective, and iii) research methods. The process of the research is discussed separately.

8.2.1 Meta-analysis of the research project

A scientific research is supposed to deliver an objective, valuable, and generic research contribution. In some research, mostly having quantitative nature, objectivity comes with thorough experimentation, and control of input variables not to mention mathematical analysis of the results. While it is merely one scientific method of the quantitative research, such methods are not suitable in this research due to the complexity of the research objects and limited numbers of them; therefore, other methods of achieving objectivity must be applied.

The initial study of the sources of objectivity and subjectivity could be beneficial for a qualitative research like this one. The meta-analysis provided sources of subjectivity to take into considerations, and sources of objectivity, the researcher – with reasonable critics – can rely on. The meta-analysis was performed and the major sources of subjectivity are described (see Section 3.4.1). This information is used to boost objectivity and to clarify aspects of the researcher's cognition and the specifics of this research process.

No specialised method to reduce the bias was used (for example, systematic literature review is one of these methods; however, due to the number of knowledge domains this type of review was not performed), which means that the researcher is unable to state the completeness and solidity of this meta-analysis. However, the author believes that these requirements are satisfied by i) the identification of the sources of objectivity and subjectivity (by identification of the objects and subjects with the relationships among them) with ii) further description of the sources of subjectivity that were considered during the research process.

An adequate result from the meta-analysis can be achieved at the end of a research project, especially one that is performed by a researcher who is not a mature research (does not have vast experience in researching a particular domain) – the majority of PhD students. The rationale behind this statement is based on the a) duration of the research process, which is b) novel to the researcher, and is filled with c) learning of a new concepts, methods, etc. All these factors affect and change the personality of the researcher – the filter and interpreter of the research results. This type of meta-analysis looks beneficial for a researcher however, it is not necessary relevant for a particular project, and the author has no expertise to estimate the relevance for this project. It felt 'right thing to do', but it may feel this way because of the information technology background of the researcher, and this meta-analysis may be viewed as a loose version of a systems analysis, which is adapted for this project.

8.2.2 Research aim and objectives

The research aim focuses a research project and the research objectives shape a research project. An initial focus and shape of this research project was defined in the research proposal, which was further agreed by the sponsoring institutions – Tata Steel Europe and EPSRC. The researcher was selected for this project and after literature review defined research objectives that are both correspond with the expectations of funding institutions and lead to relevant knowledge contributions.

The objectives define a desirable outcome. A researcher selects methods to achieve this outcome. The researcher considered various options and selected the most appropriate for the scope of the project. However, even with the study of the relevant literature, these selections are biased by the researcher's understanding of the studied material and scope. The selections satisfy the objectives and the researcher. However, they are not absolute as the researcher has no knowledge how absolute, an ideal solution can be achieved. The author expects to have this thesis as an adequate explanation of a scientific study.

8.2.3 Research strategy

The function of a research strategy is to define a research environment that leads to the adequate research results. The research strategy of this project is formulated in four principles, 1) initial agreements are a must, 2) results must be valid, 3) the scope must be understood, and for this research 4) parts of a project should complement each other. While other researchers might have different preferences for research principles, the author hardly believes that any scientist would insist on using the opposites to these four principles (i.e. fake initial agreements, invalid results, misleading scope, and conflicting parts).

These principles are defined because of the author's understanding of the applied research that is sponsored by the company. In projects like this one, science is a powerful servant to the industry, which in itself is a servant to the society (see Section 3.4.2). That means that the initial agreements must be addressed. However, these agreements must be validated to clarify the necessity of this research.

Validation of the initial agreements, results and methods is another principle of this research. Validation is performed in order to provide objective and trustworthy results to the reader, the results that are both useful for the industry and novel to science.

The selection of the right methods and solutions comes with understanding of the scope of the research. It allows the researcher to select research methods that are appropriate for a research, for example, due to high variability of DES models and small number of such models, participant observation is far more suitable than structured observation. Research objects and subjects do influence the research process and results. Understanding the scope would clarify the impact of each object/subject to the research, and if this impact negatively reflects the objectivity of the research, this understanding might neutralise the negative impact.

8.2.4 Research methods

The research methods deliver the level of accuracy and objectivity that is adequate for a scientific research. A variety of research methods were developed by academia the past years, decades and centuries. The methods are selected based on the scope of a research project and this project is not different from others in this aspect. This is a multi-disciplinary applied research having a relatively rare and complex research object – discrete event simulation models. Relatively rare means that the studied DES models count in units instead of dozens or hundreds, while complexity means a large number of variables, i.e. the real-world environment to simulate, purpose of a simulation study, people involved, depths of the study. These specifics limit the research methods that might be used in this research.

For example, case studies are selected instead of logical-mathematical study or thorough experiments. Unstructured interviews – instead of structured interviews and surveys. Participant observation – instead of structured observation. Obviously, the literature review was performed prior the study of real-world objects.

8.3 Contributions

8.3.1 Generic comment on using DES for PPS

A detailed DES model represents complex behaviour of a production system and, especially with the power of animation, provides great insights into a production process, not to mention experiments with production processes and production plans. However, the development of detailed models requires a significant amount of time. This affects DES project in two ways. Firstly, a customer would not receive results within a short period of time, which decreases business use of such models. Secondly, even if a business has a significant problem that cannot be solved with different approaches (expert opinion, linear modelling), a customer could, and probably would, initiate changes of the initial requirements of a DES modelling project, increasing the complexity of a simulation model and extending the project's time.

If this model was designed for regular and continuous use as components of management information system, this additional complexity, in combination with promotions, etc., would complicate the support of such a model and decrease its quality. Having these factors in mind, the author believes that the detailed DES models should not be developed for large production areas, especially for the cases of continuous use of such models. This states that, considering structure from Figure 2.1, big companies should not use detailed DES models for master planning as well as custom, production and distribution planning for big areas. However, master planning may benefit from the use of generic DES models, or generic DES models of big production areas that incorporate detailed models of small production areas if necessary, planning and management. Therefore, high level architecture is recommended for the study beforehand. Obviously, technologies for automatic or semi-automatic development and modification of DES models would change the situation.

8.3.2 Improving production performance using DES & GA

The author identified five approaches for improving production performance using DES & GA, namely, time-sequenced introduction of products, dispatching rules, production parameters, production site's layout, and composite. This list is relevant for researchers and engineers who are aiming to improve production performance as it directs the practitioners with available methods of optimisation. The author believes that this classification has broader use than DES & GA and may be treated as simulation modelling & meta-heuristic optimisation.

8.3.3 Optimisation of PPS using DES & GA

The first method, time-sequenced introduction of products was used in this research. The original method, as described in the literature is used for the optimisation of production schedules. This research describes a modification of this method that allows optimisation of production plans and schedules. The modified version was compared with 'standard' on three case studies.

The case studies show different Pareto frontiers, which means that each DES model is a separate optimisation problem; therefore, meta-heuristic optimisation techniques such as genetic algorithms are the appropriate choice for optimisation.

The modified version provides better results than the 'standard' one in two cases out of three (see Figure 5.15). However, the third case study (see Section 4.2.5) has not converged within neither 10'000 nor 50'000 evaluations, which may mean the modified version would outperform the original with a larger number of evaluations; unfortunately, 50'000 is the limit of the developed optimisation system due to an unknown memory problem. This problem may be too big or complex for GA with its current setting.

Both the modified and original optimisation worked with products of equal importance, which may not be the case in the real world. Product or order grouping is not supported either; however, in comparison with the first issue, the required constraints might be built in simulation models, and those constraints will not be biased as manual production planning may be.

Thereby, the modified method of improving production performance, time-sequenced introduction of products, is recommended as a method to optimise production plans and schedules.

8.3.4 Classification of cost estimation techniques

A classification of production cost estimation techniques for a systematic research of production cost estimation was developed. This was an interesting outcome of this research. The proposed classification defines cost estimation techniques on the basis of cost information and methods used to process this information. The basic architectures of information processing, as well as, stages of product life cycle these cost estimation techniques are used at and for also are reviewed.

8.3.5 Product family based cost estimation technique

A two-phase product family based cost estimation technique was developed. During the first phase, a simulation model of the production system calculates the resource utilisation, throughput, *etc.*. During the second phase, these values and information from the standard costing system are used for the estimation of relative costs, such as relative costs of product families and machines per tonne. While these costs may not provide accurate absolute values, these relative costs (the cost of one product in comparison to the cost of another product) are accurate and support argumentative decision making for production planning, sales and other domains with the requirement of knowing the cost diversification of products.

This cost estimation technique has two major advantages over other cost estimation techniques. Firstly, it works when traditional cost information is unavailable, i.e. lack of cost rates or unreliable historical costs of similar products. Secondly, it is designed to fit standard costing system, while other estimates from other cost estimation techniques may and probably would contradict values from the standard costing system.

Other cost estimation techniques are useless or cannot be trusted or contradict the standard costing system. Cost estimation techniques such as tolerance-based techniques are useless for the steel making industry. Analogy based or neural network based cost estimation techniques cannot be trusted as their known costs are mistrusted. Activity-based, operation-based or detailed cost estimation techniques may and probably would contradict the standard costing system. If a company would not simultaneously use contradicting techniques (sometimes companies use few cost estimation techniques for more argumentative decision making) or initiate massive change to another costing system, then a company has no other options but stay with standard costing system or apply product family based cost estimation technique.

This cost estimation technique was developed to add accuracy for important products while keeping standard costing system in operation. Values of other cost estimation techniques may contradict with standard costing system, and it is highly unlikely that this big enterprise, Tata Steel Europe, would change to accurate cost estimation technique (activity-based or detailed) as the costs of this change would be enormous.

However, the development of discrete event simulation models is a time-consuming process; therefore, it is feasible to apply this technique for the production areas of important products. While DES modelling was used in the first phase of estimation in this research, DES is not the only technique that is capable of calculating utilisation and throughput for a given production plan. Obviously, DES has some advantages over other modelling techniques (validity of results, accuracy in complex cases) however linear modelling or system dynamics or agent based modelling or real-life data from resource-management systems may be used during the first phase.

8.3.6 Information collection process

The author developed a process of information collection for further development of DES models of production systems that are capable of cost estimation. This process is based on activity-based costing and value stream mapping. The developed process is intuitive for production engineers, which would support the involvement of production engineers, manufacturing managers and other sources of information into DES modelling project. Education of information sources on some concepts of lean manufacturing is an unexpected outcome of using this process in the company.

This method is based on well-established methods from other domains, therefore, it provides the required functionality. Case studies and interviews correspond with this reasoning, with a notion that an over-structured process may interrupt the natural flow of conversation, and therefore, damage information gathering. The experts also mentioned that the developed prototype would benefit from visual aids. The researcher also expects a positive outcome from a web-based interface that supports parallel information collection, and other 'standard' functionality, such as, automated data backup.

8.4 Business implementation and alternative use

8.4.1 Improving production performance using DES & GA

The author identified five methods for improving production performance using DES & GA, namely, time-sequenced introduction of products, production parameters, dispatching rules, production site's layout, and composite. These methods have different applicability due to volume and cost of organisational changes.

Section 2.4.3 illustrates that changing time-sequenced introduction of products even into a simple production system changes the performance of this production system. Any production company has a number of operations that are used to process products; therefore, time-sequenced introduction of products is a generic method to improve production performance. This method was selected for this research because of this reason in combination with the direct relation of this method to production scheduling.

The second method, optimisation of production parameters is as generic as the first method yet requires detailed DES models to adjust production processes for different products. In addition, the first two methods require limited changes on small production areas (for example, manufacturing managers who submit 'standard operational procedures' to job-shop supervisors, or planning teams who submit production plans to job-shop supervisors); due to these reasons these methods are recommended for a wide industrial use.

Optimisation of dispatching rules and production sites' layouts require larger organisational changes, therefore, they are recommended for occasional industrial use; however, warehouses or companies with advanced manufacturing systems or consulting companies working on the field may use these methods on a continuous basis. These changes would affect operational management and personal retraining on various departments; the change may contradict to the companies' biases. Therefore, these methods could succeed with the support from top management.

The fifth method is a combination of two or more methods therefore, they must be treated based on the methods involved.

8.4.2 Optimisation of PPS

The production planning teams, sales, and simulation modelling engineers are the major actors of the optimisation system, each having a role and use of the system. The planning teams use the system for development of sets of nearly-optimal production plans and schedules. The sales teams check if it is feasible to produce an order within a particular period of time. Simulation engineers keep simulation models up to date.

A simulation model – the basis of the optimisation system – represents a small production area. The developed schedules would influence the related production areas. If the optimisation system would be released for regular use, then, the selection from the sets of nearly-optimum production schedules would be the major change in the planning process.

Currently, the sales team has limited information on how their decisions would affect the production areas. With the optimisation system, they would be able to experiment with new orders prior to making a request for production within a time-period. This could positively influence the delivery time and would cut down situations of assembling a critical order with products from not critical orders – a negative self-sustained practice. The reduction of stock and the related acceleration of the money flow would be an additional possible benefit.

A simulation model must represent a real situation in the production system in order to generate realistic production schedules. This means that a simulation model must be kept up to date. A simulation model can be kept up to date with either the specialists from the production business unit or specialists from RD&T; regardless of the selection a planning & scheduling advisor may benefit the company. Assuming that this optimisation system will be widely used; the author suggests a single and powerful server location that would service a variety of production business units. This option would provide qualitative support to simulation modelling and further improvement of the optimisation system.

8.4.3 Product family based cost estimation

Production management, continuous improvement, sales and simulation modelling engineers are the major actors of product family based cost estimation technique. The production management and continuous improvement would have accurate production costs, this information may be further used for cost optimisation of production systems. Sales would be able to differentiate products by costs. Simulation modelling engineers, as in the case with the optimisation system, must support simulation models for further cost estimations.

Production management and continuous improvement people would use the technique for estimating costs of production processes. Production costs are essential information for cost reduction; thereby, application of this technique would allow systematic cost reduction activities.

Currently, sales have limited information on the costs of the products, which means that they are unable to calculate profit from an order. Having accurate costs, they will be able to adjust prices and move towards maximal profit. Obviously, the product cost is not the only criterion for price definition; for example, market demand and the requirement to keep an important customer may even result in money lose for some products. However, knowledge of costs would make decision making more solid.

This technique can be used in two different ways. The first option is related to continuous real-life use when costs are estimated for actual production plans. This option would require continuous use of simulation models by planning and sales. The second option is related to trends in production plans due to internal and external factors (a seasonable marketing trend), a table of costs for typical production plans may be generated, and costs as well as throughput can be developed for further use. This table would speed-up the cost estimation and the decision-making processes.

Categorisation of products into product families can be more generic or, in opposite, more detailed. The current version of the technique differentiates products by a unique combination of machines however without considering the sequence of processing in machines. If more generic combination is required, then 'similar' product families may be merged or machines having the same functionality may be combined into one category or any other option that satisfies a company that utilises this technique. Categorisation may be more detailed, as product families may form sub-groups on the basis of some characteristics of products. However, both generalisation and detalisation must be supported with an adequate simulation model.

Discrete event simulation models were used in the first phase in this research. The function of these models and the phase is to provide adequate values of utilisation and throughput from production schedules. DES has some advantages; however, other simulation modelling techniques (linear modelling, system dynamics, agent based modelling) are also capable of providing such values; therefore, they can be used in the first phase. If a company has adequate resource management system or collects production statistics, real-life data can be used as the first phase in the absence of simulation models.

A simple sequential production system having three machines, two resources, and four product families was used in the first example (see Section 6.5.1). A discrete event simulation model was developed to represent this hypothetical system; however, a 'light' linear simulation model, instead of a 'heavy' discrete event simulation model. Another example (see Section 6.5.1) however is more complex and complexity requires adequate methods of simulation modelling. DES is capable of providing accurate estimates in complex cases; however, it has a negative side, as the development of a DES model is a time-consuming process.

The second phase also has some room for adaptation to the scope of a particular company. In the described technique, costs of paid and unused fixed resources are divided between products in proportion of a number of machines that use each resource and a number of product families that are processed by a particular machine. However, a company may find another proportion more useful, for example, by adding values of resource consumption by each particular machine.

8.4.4 Information collection process

Production management and engineering, continuous improvement and workers, as well as, simulation engineers are the major actors of the information collection process. While simulation engineers may use collected information to develop simulation models, the rest provides information on a single or multiple occasions.

This information collection process incorporates few important concepts. Firstly, the nature of information. The process is based on value stream mapping and activity-based costing processes; this information is adequate for further development of simulation models of production systems that are capable of cost estimation. Secondly, the sequence of the collected information, which is based according to VSM, ABC and information providers. Thirdly, this process is based on concepts from lean manufacturing (VSM, product families, etc.); therefore, it is intuitive to the information providers, who mostly work in production. An iterative nature of simulation model development means that a simulation engineer would collect the required amount of information.

8.5 Advantages and limitations

Each contribution to the knowledge of this research project, namely, classification of cost estimation techniques, process of information collection, product family based cost estimation technique, and production planning and scheduling optimisation using time-sequenced type of chromosome, have some academic and industrial advantages and disadvantages.

The classification of production cost estimation techniques is based on basic components – cost information, methods to process this information and architectural features – that makes this classification universal as it can be applied to any cost estimation technique, and if not – it can be easily expanded by adding a new method of information processing. However, this classification would have academic use only if the academia would start using it. Moreover, this classification has use for either researchers working on information processing in cost estimation, or research institutions systematically bidding for grants in the area of cost estimation research. This classification has limited use for the rest of the research community.

This classification do not have primary use for the industry; however, it provides a mindset, that a company may develop a cost estimation technique that fits the company's specifics. Product family based cost estimation technique is an example of a specialised technique developed for Tata Steel Europe with its standard costing system.

A process of information collection is useful for inexperienced simulation engineers, yet would limit experienced ones. The basis of this process on activity-based costing suggests that this process would be useful for collecting cost information and value stream mapping – for collecting information about a production system and would be intuitive for production engineers, manufacturing managers, and other major information sources. However, even though it is based on well-established methods, the research lacks quantitative scientific evidence that this process is useful for a company. If production engineers are not familiar with lean manufacturing concepts, some of them will be learned during the process of information collects.

This process addresses majority of the issues related to the factors that affect simulation models. This has been achieved through a) prompting a user to define objectives and scope of a project, b) an intuitive terminology and structure to the major information sources, c) support of an iterative process, and d) storing this information in an electronic storage. This process and tool may or may not reduce data collection and conceptual modelling stage of the project. Due to the limited amount of resources, a web interface supporting parallel information collection was not developed. Even if it would be developed, an appropriate answer to this question could be given only after a comparison of a variety of different DES modelling projects with and without using this process.

Product family based cost estimation technique is designed to fit Tata Steel Europe management and production specifics, i.e. standard costing system and complex production systems. This technique can be applied without changes in the management system, would not affect standard costing system except areas it is directly applied; that makes this cost estimation technique a natural choice for the company. However, the application of this technique is limited as simulation models are required prior to the use of this technique. DES modelling is a time-consuming process and may be afforded on crucial areas only. However, identifying these crucial areas is not researched in this project. Speaking about academic value of this cost estimation technique, it is worth mentioning that this cost estimation technique is novel to the research community, and illustrates an example of accurate production cost estimation in situation, where no accurate cost information is available.

Production planning and scheduling share the same limitations with the cost estimation technique, as it is also based on DES models (or any other simulation modelling), and can be applied on crucial areas only. In addition to this, planning and scheduling within one area will affect other production areas and no tools were developed to track this. However, a combination of DES modelling with GA for production scheduling is a generic tool capable of developing sets of nearly-optimal production plans in complex production environments. And application of this combination would improve the confidence of production planners. A DES model that can provide different outputs can be used as objectives of GA, changing these objectives may result in the optimisation of energy consumption in one case, and high throughput on another case; this variability of DES with GA is an interesting aspect of this type of production planning. A concept of using time sequenced introductions for production planning in addition to production scheduling and comparison between PPS with scheduling, provide academic value to this part of the research.

8.6 Conclusions

The research has achieved all the objectives identified in Chapter 3:

1. *To investigate state of the art use of DES in steel manufacturing and how cost estimation is performed withing the environment.* Discrete event simulation is used for various operations management problems, the majority of DES models are not used on continuous basis. Production planning and scheduling is done using mental and software systems, planning teams are not aware if the plans and schedules are optimal; an optimisation system for production planning and scheduling would solve this issue. Standard costing operates average annual costs, which means no accurate costing for products and orders; therefore, a new approach to cost estimation is required to solve issues with price management. This is in detail described in Chapter 4.

2. To identify the industrial practice and challenges in use of DES in steel manufacturing. Chapters 2 and 4 provide information about DES modelling practices in steel manufacturing. Simulation models are created to find a solution for various issues related to operations management. An active use of the proposed optimisation and cost estimation frameworks would result active development of DES models. Conceptual modelling is a critical area for improvement, especially with the proposed use of DES modelling.

3. Develop a framework to use DES for planning and scheduling optimisation. Five approaches to improve production performance using DES&GAs have been identified, and time-sequenced introduction of products was selected for this research. Previously it was used for optimisation of production schedules, in this research it was adapted for simultaneous optimisation of production plans and schedules. This chromosome was successfully validated using industrial case studies. A meta-heuristic approach to optimisation should be used in such optimisation systems because each DES model may be treated as a separate optimisation problem. Some production plans and schedules would be challenging to optimise because of parameters of GA (e.g. population size) and solution (e.g. chromosome length). This is in detail described in Chapter 5.

4. Develop an improved cost estimation framework for steel manufacturing using DES environment. The proposed cost estimation technique is capable of accurate cost estimation and benefits standard costing system in use in the company. This cost estimation technique can utilise data from various information sources, e.g. DES model or operations management software. The technique estimates processing costs only, e.g. overhead or material costs are not included. The technique estimates costs for product families, it requires more than one product family in production plan for cost estimation. The cost estimation technique fits the developed classification of cost estimation techniques; therefore, this classification can be used for systematic research of production cost estimation techniques. This is in detail described in Section 2.3 and Chapter 6.

5. Develop a framework for information collection to support DES model development of production systems in steel manufacturing. This research has demonstrated that a process of structured information collection can be used for development of conceptual models. The proposed process is suited to guide inexperienced simulation engineers in development of DES models capable of cost estimations. This is in detail described in Chapter 7.

6. Perform a systematic validation of frameworks using real life case studies. All frameworks pass systematic validation. Theoretical, realisation, and empirical parts of the research were separately validated on super-system, system, and sub-system levels. Real life case studies successfully validated each proposed framework. This is in detail described in Sections 5.3, 6.6, and 7.3.

Major conclusions from the research are as follows:

- Notwithstanding the considerable amount of research in production planning and scheduling (PPS), simultaneous optimisation of production plans and schedules for steelmaking has not been addressed before.

- Current practice of using standard costing needs improvement to calculate costs for each product family.

- Cost estimation in the steel manufacturing company needs improvement because of the current lack of accurate costs of product families that affects quality of price management.

- Discrete event simulation can improve the accuracy of PPS and cost estimation for complex production systems.

- DES-driven PPS and cost estimation would increase demand for DES models

- Conceptual modelling needs to be improved in order to achieve model development efficiency and to make the process less reliant on practitioners' experience and capabilities.

- GA and DES based optimisation approach can be used to perform multi-objective optimisation of plans and schedules simultaneously.

- PPS optimisation for some production areas provides a challenging problem to GAs, as evidenced by optimisation case study 2.

- The developed cost estimation technique is capable of providing accurate cost for product families.
- The cost estimation technique would be useful for companies operating on volume-driven manufacturing processes rather than on unit-driven.
- A formal information collection process can aid conceptual modelling of production systems and support development of DES models for cost estimation.

8.7 Recommendations to the company

8.7.1 Optimisation of production plans and schedules

The current optimisation system has numerous issues preventing industrial use of the system. For example, optimisation runs require manual operations, one optimisation can be run at a time, optimisation results require additional information processing, optimisation runs on a local machine, optimisation system consists of a number of modules connected with fragile interfaces, simulation models should be specially prepared for optimisation.

The author suggests further development of the optimisation framework. The company would benefit from a centralised optimisation center because this type of optimisation is case-based, development of off-the-shelf software would require additional effort, and setup would require advanced IT skills. This optimisation system should provide comprehensive analysis tools and interfaces to some of the current production planning, manufacturing management, sales and dispatching systems.

The author expects the following scenario. RD&T BU develops a discrete event simulation model for a production BU. RD&T BU suggests re-use of this DES model as a part of production planning and scheduling optimisation system. The model is modified for this purpose, becomes a part of the optimisation system, interfaces between this and other business software are developed and setup. RD&T provides educational and support services to the production BU.

8.7.2 Cost estimation

The current cost estimation system has a number of issues preventing industrial use of the system. For example it consists of two separate modules having no computer interfaces, manual data transfer from a DES model to MS Excel spreadsheet, development of MS Excel spreadsheet is done manually, development requires good understanding of the cost estimation technique, cost estimation runs (within one cost estimation study) are not automated.

The author suggests further development of the cost estimation framework. The company would benefit from an off-the-shelf cost estimation software that can be easily setup regardless of the nature of a tool providing resource utilisation. It can be Arena DES model, Witness DES model, Flexim DES model, or a running operations management software. The latter case however may require additional services from RD&T BU.

The author expects the following scenario. RD&T BU provides a new tool for cost estimation and runs a services supporting this tool. RD&T BU advertises the tool to production BUs. At the end of each DES modelling project RD&T BU suggests to re-use the simulation model for cost estimation and supports modification of the model if necessary.

8.7.3 Information collection

The current information collection system has various issues preventing industrial use of the system. For example, it is a single user tool therefore preventing information collection from various sources, it runs on a local machine and requires a proprietary software, it does not support a multimedia component.

The author suggests further development of the information collection framework. The company would benefit from a Web 2.0 solution allowing to collect information for further development of DES models. Automation of DES models from the developed information might be an advantageous capability.

The author expects the following scenario. RD&T BU uses this tool during each DES modelling project for information collection, and also suggests it to simulation engineers from production BUs. At the end of each project, the developed simulation model and related data are uploaded to the tool.

8.8 Future research

The topics for future research are listed for each contribution of this research, namely, 1) a classification of methods to improve performance of production systems using DES & GA, 2) optimisation of production plans and schedules, 3) classification for systematic research of production cost estimation techniques, 4) novel product family based cost estimation technique, and 5) process of information collection for further development of DES models that are capable of cost estimation.

Classification of methods to improve the performance of production systems would significantly benefit from a thorough literature review on: different meta-heuristic and simulation modelling methods, of various aspects of production system (production, maintenance, logistics, storage, etc), including, different types of organisation of such aspects.

Optimisation of production plans and schedules would benefit from a comprehensive classification of discrete event simulation models of production systems (as different types of optimisation problems, complexity or variability issues, etc.); this classification could have helped to explain the results of case study 2. A composite method to improve production performance or/and comparison of different GAs are interesting areas for research.

Classification for systematic development of cost estimation research is a natural point for the development of a standard procedure of cost estimation technique for the scope of a company.

Product family based cost estimation technique would benefit from numerical comparison with other cost estimation techniques, as well as its improvement if traditional costs are partially available (this could improve the accuracy of absolute costs). Different simulation modelling methods (which are used in the first phase of estimation) may be compared to the accuracy of the estimates.

The process of information collection would benefit from incorporating High Level Architecture into the process, and automated or semi-automated development of DES models. Additional research is required in the area of decision support system for simulation model development.

Bibliography

[1] J. Banks, J. S. Carson, B. L. Nelson, D. M. Nicol, Discrete-event systems simulation, fourth edition Edition, Pearson Prentice Hall, 2005.

[2] P. Siebers, C. MacAl, J. Garnett, D. Buxton, M. Pidd, Discrete-event simulation is dead, long live agent-based simulation!, Journal of Simulation 4 (3) (2010) 204–210.

[3] A. Tako, S. Robinson, Comparing model development in discrete event simulation and system dynamics, Austin, TX, 2009, pp. 979–991, cited By (since 1996) 0; Conference of 2009 Winter Simulation Conference, WSC 2009; Conference Date: 13 December 2009 through 16 December 2009; Conference Code: 80063.

[4] (accessed 24th May 2011), http://www.tatasteeleurope.com/en/.

[5] (accessed 24th May 2011), http://www.eef.org.uk/uksteel/about-the-industry/how-steel-is-made/default.htm.

[6] S. Robinson, Discrete-event simulation: from the pioneers to the present, what next?, Journal of the Operational Research Society 56 (2005) 619–629.

[7] S. Robinson, Conceptual modelling for simulation part i: definition and requirements., Journal of the Operational Research Society 59 (2008) 278–290.

[8] S. Robinson, Conceptual modelling for simulation part ii: a framework for conceptual modelling., Journal of the Operational Research Society 59 (2008) 291–304.

[9] K. Deb, Multi-objective optimization using evolutionary algorithms, John Wiley & Sons, Ltd, 2001.

[10] C. Acquah, I. Datskov, A. Mawardi, F. Zhang, L. Achenie, R. Pitchumani, E. Santos, Optimization under uncertainty of a composite fabrication process using a deterministic one-stage approach, Computers and Chemical Engineering 30 (6-7) (2006) 947–960.

[11] R. Paul, T. Chanev, Simulation optimisation using a genetic algorithm, Simulation Practice and Theory 6 (6) (1998) 601–611.

[12] M. Andersson, A. Ng, H. Grimm, Simulation optimization for industrial scheduling using hybrid genetic representation, in: 2008 Winter Simulation Conference, WSC 2008, Miami, FL, 2008, pp. 2004–2011.

[13] H. Meyr, M. Wagner, J. Rohde, Supply chain management and advanced planning: Concepts, models software and case studies, 2nd Edition, Springer-Verlag, Berlin, 2002.

[14] C. Maravelias, C. Sung, Integration of production planning and scheduling: Overview, challenges and opportunities, Computers and Chemical Engineering 33 (12) (2009) 1919–1930.

[15] G. Salvendy (Ed.), Handbook of industrial engineering: technology and operations management, A Wiley-Interscience publication, 2001.

[16] D. Lei, Multi-objective production scheduling: A survey, International Journal of Advanced Manufacturing Technology 43 (9-10) (2009) 925–938.

[17] D.-B. Tang, L. Zheng, Z.-Z. Li, An intelligent feature-based design for stamping system, International Journal of Advanced Manufacturing Technology 18 (3) (2001) 193–200.

[18] G. Dutta, R. Fourer, A survey of mathematical programming applications in integrated steel plants, Manufacturing and Service Operations Management 3 (4) (2001) 387–400.

[19] R. As'ad, K. Demirli, Production scheduling in steel rolling mills with demand substitution: Rolling horizon implementation and approximations, International Journal of Production Economics 126 (2) (2010) 361–369.

[20] L. Tang, J. Guan, G. Hu, Steelmaking and refining coordinated scheduling problem with waiting time and transportation consideration, Computers and Industrial Engineering 58 (2) (2010) 239–248.

[21] Y.-C. Xue, D.-L. Zheng, Q.-W. Yang, Optimum steel making cast plan with unknown cast number based on the modified discrete particle swarm optimization, Kongzhi Lilun Yu Yinyong/Control Theory and Applications 27 (2) (2010) 273–277.

[22] L. Tang, X. Wang, A two-phase heuristic for the production scheduling of heavy plates in steel industry, IEEE Transactions on Control Systems Technology 18 (1) (2010) 104–117.

[23] L. Tang, X. Wang, Simultaneously scheduling multiple turns for steel color-coating production, European Journal of Operational Research 198 (3) (2009) 715–725.

[24] L. Tang, X. Wang, J. Liu, Color-coating production scheduling for coils in inventory in steel industry, IEEE Transactions on Automation Science and Engineering 5 (3) (2008) 544–549.

[25] A. Atighehchian, M. Bijari, H. Tarkesh, A novel hybrid algorithm for scheduling steel-making continuous casting production, Computers and Operations Research 36 (8) (2009) 2450–2461.

[26] C. Pan, G. Yang, A method of solving a large-scale rolling batch scheduling problem in steel production using a variant of column generation, Computers and Industrial Engineering 56 (1) (2009) 165–178.

[27] M. Vanhoucke, D. Debels, A finite-capacity production scheduling procedure for a belgian steel company, International Journal of Production Research 47 (3) (2009) 561–584.

[28] H. Missbauer, W. Hauber, W. Stadler, A scheduling system for the steelmaking-continuous casting process. a case study from the steel-making industry, International Journal of Production Research 47 (15) (2009) 4147–4172.

[29] X. Wang, L. Tang, Integration of batching and scheduling for hot rolling production in the steel industry, International Journal of Advanced Manufacturing Technology 36 (5-6) (2008) 431–441.

[30] L. Tang, X. Wang, A predictive reactive scheduling method for color-coating production in steel industry, International Journal of Advanced Manufacturing Technology 35 (7-8) (2008) 633–645.

[31] M. Mathirajan, V. Chandru, A. Sivakumar, Heuristic algorithms for scheduling heat-treatment furnaces of steel casting industries, Sadhana - Academy Proceedings in Engineering Sciences 32 (5) (2007) 479–500.

[32] P. Huegler, F. Vasko, Metaheuristics for meltshop scheduling in the steel industry, Journal of the Operational Research Society 58 (6) (2007) 791–796.

[33] T. Tanizaki, T. Tamura, H. Sakai, Y. Takahashi, T. Imai, A heuristic scheduling algorithm for steel making process with crane handling, Journal of the Operations Research Society of Japan 49 (3) (2006) 188–201.

[34] J. Li, L. Li, L. Tang, H. Wu, A case of rule-based heuristics for scheduling hot rolling seamless steel tube production, Expert Systems 23 (3) (2006) 145–158.

[35] T.-C. Chen, An application of lagrangean decomposition to the scheduling of hot charged rolling in steel production, WSEAS Transactions on Mathematics 5 (7) (2006) 785–793.

[36] V. Kumar, S. Kumar, M. Tiwari, F. Chan, Auction-based approach to resolve the scheduling problem in the steel making process, International Journal of Production Research 44 (8) (2006) 1503–1522.

[37] P. Appelqvist, J.-M. Lehtonen, Combining optimisation and simulation for steel production scheduling, Journal of Manufacturing Technology Management 16 (2) (2005) 197–210.

[38] K. Singh, Srinivas, M. Tiwari, Modelling the slab stack shuffling problem in developing steel rolling schedules and its solution using improved parallel genetic algorithms, International Journal of Production Economics 91 (2) (2004) 135–147.

[39] R. Roy, B. Adesola, S. Thornton, Development of a knowledge model for managing schedule disturbance in steel-making, International Journal of Production Research 42 (18) (2004) 3975–3994.

[40] D. Ouelhadj, S. Petrovic, P. Cowling, A. Meisels, Inter-agent cooperation and communication for agent-based robust dynamic scheduling in steel production, Advanced Engineering Informatics 18 (3) (2004) 161–172.

[41] B. Neureuther, G. Polak, N. Sanders, A hierarchical production plan for a make-to-order steel fabrication plant, Production Planning and Control 15 (3) (2004) 324–335.

[42] P. Cowling, D. Ouelhadj, S. Petrovic, Dynamic scheduling of steel casting and milling using multi-agents, Production Planning and Control 15 (2) (2004) 178–188.

[43] L. Tang, J. Liu, A. Rong, Z. Yang, Modelling and a genetic algorithm solution for the slab stack shuffling problem when implementing steel rolling schedules, International Journal of Production Research 40 (7) (2002) 1583–1595.

[44] H. Park, Y. Hong, S. Chang, An efficient scheduling algorithm for the hot coil making in the steel mini-mill, Production Planning and Control 13 (3) (2002) 298–306.

[45] L. Tang, P. Luh, J. Liu, L. Fang, Steel-making process scheduling using lagrangian relaxation, International Journal of Production Research 40 (1) (2002) 55–70.

[46] T. Van Voorhis, F. Peters, D. Johnson, Developing software for generating pouring schedules for steel foundries, Computers and Industrial Engineering 39 (3-4) (2001) 219–234.

[47] R. Roy, P. Souchoroukov, T. Griggs, Function-based cost estimating, International Journal of Production Research 46 (10) (2008) 2621–2650.

[48] R. Roy, S. Hinduja, R. Teti, Recent advances in engineering design optimisation: Challenges and future trends, {CIRP} Annals - Manufacturing Technology 57 (2) (2008) 697 – 715.

[49] D. J. Stockton, L. Quinn, R. A. Khalil, Use of genetic algorithms in operations management: Part 1: Applications, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 218 (3) (2004) 315–327.

[50] D. J. Stockton, L. Quinn, R. A. Khalil, Use of genetic algorithms in operations management: Part 2: Results, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 218 (3) (2004) 329–343.

[51] D. Stockton, R. Khalil, J. Ardon-Finch, Control point policy optimization using genetic algorithms, International Journal of Production Research 46 (10) (2008) 2785–2795.

[52] C. Azzaro-Pantel, L. Bernal-Haro, P. Baudet, S. Domenech, L. Pibouleau, A two-stage methodology for short-term batch plant scheduling: discrete-event simulation and genetic algorithm, Computers and Chemical Engineering 22 (1998) 1461–1481.

[53] N. Oldenburg, G. Gruhn, J. Stoldt, Capacity analysis of multi-product plants integrating energy consumption, Applied Thermal Engineering 21 (13-14) (2001) 1283–1298.

[54] J. Tedford, C. Lowe, Production scheduling using adaptable fuzzy logic with genetic algorithms, International Journal of Production Research 41 (12) (2003) 2681–2697.

[55] Q.-L. Liu, W. Wang, H.-R. Zhan, Z.-G. Wang, R.-G. Liu, Optimal scheduling method for a bell-type batch annealing shop and its application, Control Engineering Practice 13 (10) (2005) 1315–1325.

[56] D.-P. Song, Raw material release time control for complex make-to-order products with stochastic processing times, International Journal of Production Economics 103 (1) (2006) 371–385.

[57] A. Alfieri, Workload simulation and optimisation in multi-criteria hybrid flowshop scheduling: A case study, Int J Prod Res 47 (18) (2009) 5129–5145.

[58] G. Cavory, R. Dupas, G. Goncalves, A genetic approach to the scheduling of preventive maintenance tasks on a single product manufacturing production line, International Journal of Production Economics 74 (1-3) (2001) 135–146.

[59] K. Caskey, R. Storch, Heterogeneous dispatching rules in job and flow shops, Production Planning & Control 7 (4) (1996) 351–361.

[60] E. Gaury, H. Pierreval, J. Kleijnen, Evolutionary approach to select a pull system among kanban, conwip and hybrid, Journal of Intelligent Manufacturing 11 (2) (2000) 157–167.

[61] A. Ang, A. Sivakumar, Online multiobjective single machine dynamic scheduling with sequence-dependent setups using simulation-based genetic algorithm with desirability function, in: 2007 Winter Simulation Conference, WSC, Washington, DC, 2007, pp. 1828–1834.

[62] Y. Yan, G. Wang, A job shop scheduling approach based on simulation optimization, in: Proceedings of the 2007 IEEE IEEM, 2007, pp. 1816–1822.

[63] T. Lacksonen, Empirical comparison of search algorithms for discrete event simulation, Computers & Industrial Engineering 40 (1-2) (2001) 133–148.

[64] A. Medaglia, S.-C. Fang, H. Nuttle, Fuzzy controlled simulation optimization, Fuzzy Sets and Systems 127 (2002) 65–64.

[65] R. Al-Aomar, A. Al-Okaily, A ga-based parameter design for single machine turning process with high-volume production, Computers and Industrial Engineering 50 (2006) 317–337.

[66] M. Hamada, H. Martz, E. Berg, A. Koehler, Optimizing the product-based availability of a buffered industrial process, Reliability Engineering and System Safity 91 (9) (2006) 1039–1048.

[67] T. Yang, H.-P. Fu, K.-Y. Yang, An evolutionary-simulation approach for the optimization of multi-constant work-in-process strategy - a case study, International Journal of Production Economics 107 (2007) 104–114.

[68] J. Cochran, H. Kaylani, Optimal design of a hybrid push/pull serial manufacturing system with multiple part types, International Journal of Production Research 46 (4) (2008) 949–965.

[69] F. Dugardin, F. Yalaoui, L. Amodeo, New multi-objective method to solve reentrant hybrid flow shop scheduling problem, European Journal of Operational Research 203 (1) (2010) 22–31.

[70] S. V. Volsem, W. Dullaert, H. V. Landeghem, An evolutionary algorithm and discrete event simulation for optimizing inspection strategies for multi-stage processes, European Journal of Operational Research 179 (2007) 621–633.

[71] Z. Yang, D. Djurdjanovic, J. Ni, Maintenance scheduling in manufacturing systems based on predicted machine degradation, Journal of Intelligent Manufacturing 19 (2008) 87–98.

[72] A. Oyarbide-Zubillaga, A. Goti, A. Sanchez, Preventive maintenance optimisation of multi-equipment manufacturing systems by combining discrete event simulation and multi-objective evolutionary algorithms, Production Planning & Control 19 (4) (2008) 342–355.

[73] G. Yuriy, N. Vayenas, Discrete-event simulation of mine equipment systems combined with a reliability assessment model based on genetic algorithms, International Journal of Mining, Reclamation and Environment 22 (1) (2008) 70–83.

[74] A. Sarmiento, L. Rabelo, R. Lakkoju, R. Moraga, Stability analysis of the supply chain by using neural networks and genetic algorithms, in: 2007 Winter Simulation Conference, WSC, Washington, DC, 2007, pp. 1968–1976.

[75] L. Bernal-Haro, C. Azzaro-Pantel, S. Domenech, L. Pibouleau, Design of multipurpose batch chemical plants using a genetic algorithm, Computers and Chemical Engineering 22.

[76] S. Dedieu, L. Pibouleau, C. Azzaro-Pantel, S. Domenech, Design and retrofit of multiobjective batch plants via a multicriteria genetic algorithm, Computers and Chemical Engineering 27 (12) (2003) 1723–1740.

[77] G.-C. Vosniakos, A. Teifakis, P. Benardos, Neural network simulation metamodels and genetic algorithms in analysis and design of manufacturing cells, International Journal of Advanced Manufacturing Technology 29 (5-6) (2006) 541–550.

[78] H. Askari-Nasab, S. Frimpong, J. Szymanski, Modelling open pit dynamics using discrete simulation, International Journal of Mining, Reclamation and Environment 21 (2007) 35–49.

[79] H. Ding, L. Benyoucef, X. Xie, A simulation-optimization approach using genetic search for supplier selection, in: C. S.E., S. P.J., F. D., M. D.J. (Eds.), Proceedings of the 2003 Simulation Conference: Driving Innovation, Vol. 2, New Orleans, LA, 2003, pp. 1260–1267.

[80] H. Ding, L. Benyoucef, X. Xie, A multiobjective optimization method for strategic sourcing and inventory replenishment, in: Proceedings- 2004 IEEE International Conference on Robotics and Automation, Vol. 2004, New Orleans, LA, 2004, pp. 2711–2716.

[81] H. Ding, L. Benyouncef, X. Xie, A simulation optimization methodology for supplier selection problem, International Journal of Computer Integrated Manufacturing 18 (2005) 210–224.

[82] K. Dahal, S. Galloway, G. Burt, M. J., I. Hopkins, A case study of process facility optimization using discrete event simulation and genetic algorithm, in: GECCO'05, 2005, pp. 2197–2198.

[83] R. D. Stewart, R. M. Wyskida, J. D. Johannes (Eds.), Cost estimator's reference manual, 2nd Edition, A Wiley-Interscience Publication, 1995.

[84] K. K. Humphreys (Ed.), Project and cost engineers' handbook, 4th Edition, Marcel Dekker, 2005.

[85] P. F. Ostwald, T. S. McLaren, Cost analysis and estimating for engineering and management, Pearson Education, Inc., 2004.

[86] A. Niazi, J. Dai, S. Balabani, L. Seneviratne, Product cost estimation: Technique classification and methodology review, Journal of Manufacturing Science and Engineering 128 (2006) 563–575.

[87] R. Curran, S. Raghunathan, M. Price, Review of aerospace engineering cost modelling: The genetic causal approach, Progress in Aerospace Sciences 40 (8) (2004) 487–534.

[88] C. Rush, R. Roy, Analysis of cost estimating processes used within a concurrent engineering environment throughout a product life cycle, in: Proceedings of the 7th international conference on concurrent engineering, Technomic Publishing Co. Inc., 2000, pp. 58–67.

[89] R. Roy, Cost engineering: why, what and how?, Technical report, Cranfield University, UK (09 2003).

[90] G. Cokins, Activity-based Cost Management: An Executive's Guide, John Wiley & Sons, Inc, 2001.

[91] R. Cooper, R. Slagmulder, Activity-based cost management system architecture – part i, Strategic Finance 81 (4) (1999) 12.

[92] R. Cooper, R. Slagmulder, Activity-based cost management system architecture – part ii, Strategic Finance 81 (6) (1999) 69.

[93] A. Gayretli, H. Abdalla, Feature-based prototype system for the evaluation and optimisation of manufacturing processes, Computers and Industrial Engineering 37 (1) (1999) 481–484.

[94] P. Leibl, M. Hundal, G. Hoehne, Cost calculation with a feature-based cad system using modules for calculation, comparison and forecast, Journal of Engineering Design 10 (1) (1999) 92–102.

[95] C. Ou-Yang, T. Lin, Developing an integrated framework for feature-based early manufacturing cost estimation, International Journal of Advanced Manufacturing Technology 13 (9) (1997) 618–629.

[96] J. Rios, D2.4: Report on prototype cost engineering mentor and v-ces platform: prototype 1, Tech. rep., Cranfield University, UK (2005).

[97] N. Bernet, M. Wakeman, P.-E. Bourban, J.-A. Mánson, An integrated cost and consolidation model for commingled yarn based composites, Composites Part A: Applied Science and Manufacturing 33 (4) (2002) 495–506.

[98] P. Duverlie, J. Castelain, Cost estimation during design step: Parametric method versus case based reasoning method, International Journal of Advanced Manufacturing Technology 15 (12) (1999) 895–906.

[99] J.-Y. Jung, Manufacturing cost estimation for machined parts based on manufacturing features, Journal of Intelligent Manufacturing 13 (4) (2002) 227–238.

[100] C.-X. Feng, A. Kusiak, C.-C. Huang, Cost evaluation in design with form features, Computer-Aided Design 28 (11) (1996) 879–885.

[101] S. Cavalieri, P. Maccarrone, R. Pinto, Parametric vs. neural network models for the estimation of production costs: A case study in the automotive industry, International Journal of Production Economics 91 (2) (2004) 165–177.

[102] N. Singh, Integrated product and process design: A multi-objective modeling framework, Robotics and Computer-Integrated Manufacturing 18 (2) (2002) 157–168.

[103] S. Yeo, B. Ngoi, L. Poh, C. Hang, Cost-tolerance relationships for non-traditional machining processes, International Journal of Advanced Manufacturing Technology 13 (1) (1997) 35–41.

[104] M. Ficko, I. Drstvensek, M. Brezocnik, J. Balic, B. Vaupotic, Prediction of total manufacturing costs for stamping tool on the basis of cad-model of finished product, Journal of Materials Processing Technology 164-165 (2005) 1327–1335.

[105] M.-Y. Chen, D.-F. Chen, Early cost estimation of strip-steel coiler using bp neural network, in: Proceedings of 2002 International Conference on Machine Learning and Cybernetics, Vol. 3, Beijing, 2002, pp. 1326–1331.

[106] Y. Zhang, J. Fuh, A neural network approach for early cost estimation of packaging products, Computers and Industrial Engineering 34 (2-4) (1998) 433–450.

[107] G. S. Fishman, Concepts and methods in discrete event digital simulation, Wiley, 1973.

[108] J. Banks, Discrete-event system simulation, 4th Edition, Pearson Education International, 2004.

[109] I. Mitrani, Simulation techniques for discrete event systems, Cambridge computer science texts; 14, 1982.

[110] G. A. Wainer, Discrete-event modeling and simulation: a practitioner's approach, CRC Press, 2009.

[111] Ieee/eia standard industry implementation of international standard iso/iec 12207: 1995 (iso/iec 12207) standard for information technology software life cycle processes, IEEE/EIA 12207.0-1996 (1998) i –75.

[112] J. Miller, P. Fishwick, S. Taylor, P. Benjamin, B. Szymanski, Research and commercial opportunities in web-based simulation, Simulation Practice and Theory 9 (1-2) (2001) 55–72.

[113] B. Hollocks, Discrete-event simulation: An inquiry into user practice, Simulation Practice and Theory 8 (6-7) (2001) 451–471.

[114] E. Woodward, G. Mackulak, Detecting logic errors in discrete-event simulation: Reverse engineering through event graphs, Simulation Practice and Theory 5 (4) (1997) 357–376.

[115] N. Robertson, T. Perera, Automated data collection for simulation?, Simulation Practice and Theory 9 (6-8) (2002) 349–364.

[116] A. Greasley, Costing police custody operations, Policing 24 (2) (2001) 216–227.

[117] S. Taylor, S. Robinson, Simulation software: Evolution or revolution?, Journal of Simulation 3 (1) (2009) 1–2.

[118] S. E. Chick, Six ways to improve a simulation analysis, Journal of Simulation 1 (2006) 21–28.

[119] A. Ingemansson, T. Ylipä, G. Bolmsjö, Reducing bottle-necks in a manufacturing system with automatic data collection and discrete-event simulation, Journal of Manufacturing Technology Management 16 (6) (2005) 615–628.

[120] M. Pidd, A. Carvalho, Simulation software: not the same yesterday, today or forever, Journal of Simulation 1 (2006) 7–20.

[121] R. Cooper, The rise of activity-based costing - part one: What is an activity-based cost system?, Journal of Cost Management 2 (2) (1988) 45–54.

[122] A. Aderoba, A generalised cost-estimation model for job shops, International Journal of Production Economics 53 (3) (1997) 257–263.

[123] M. Özbayrak, M. Akgün, A. K. Türker, Activity-based cost estimation in a push/pull advanced manufacturing system, International Journal of Production Economics 87 (1) (2004) 49–65.

[124] D. Ben-Arieh, L. Qian, Activity-based cost management for design and development stage, International Journal of Production Economics 83 (2) (2003) 169–183.

[125] J. Park, T. Simpson, Development of a production cost estimation framework to support product family design, International Journal of Production Research 43 (4) (2005) 731–772.

[126] R. S. Kaplan, S. R. Anderson, Time-driven activity-based costing, Harvard Business Review 82 (11) (2004) 131–138.

[127] A. Bhimani, C. Horngren, S. Datar, G. Foster, Management and Cost Accounting, 4th Edition, Prentice Hall, 2007.

[128] C. Drury, Management and cost accounting, 6th Edition, Thomson Learning, 2004.

[129] M. Gietzmann, G. Monahan, Absorption versus direct costing: The relevance of opportunity costs in the management of congested stochastic production systems, Management Accounting Research 7 (4) (1996) 409–429.

[130] D. Boyd, L. Kronk, R. Skinner, The effects of just-in-time systems on financial accounting metrics, Industrial Management and Data Systems 102 (3) (2002) 153–164.

[131] D. Meade, S. Kumar, A. Houshyar, Financial analysis of a theoretical lean manufacturing implementation using hybrid simulation modeling, Journal of Manufacturing Systems 25 (2) (2006) 137–152.

[132] R. Göx, Strategic transfer pricing, absorption costing, and observability, Management Accounting Research 11 (3) (2000) 327–348.

[133] M. Al-Omiri, C. Drury, A survey of factors influencing the choice of product costing systems in uk organizations, Management Accounting Research 18 (4) (2007) 399–424.

[134] M. Rother, J. Shook, Learning to see, Lean Enterprise Institute, 1998.

[135] J. Bicheno, The new lean toolbox: towards facst, flexible flow, PICSIE Books, 2004.

[136] R. Detty, J. Yingling, Quantifying benefits of conversion to lean manufacturing with discrete event simulation: A case study, International Journal of Production Research 38 (2) (2000) 429–445.

[137] B. Schroer, Simulation as a tool in understanding the concepts of lean manufacturing, Simulation 80 (3) (2004) 171–175.

[138] J. Narasimhan, L. Parthasarathy, P. Narayan, Increasing the effectiveness of value stream mapping using simulation tools in engine test operations, in: 18th IASTED International Conference on Modelling and Simulation, MS 2007, Montreal, QC, 2007, pp. 260–264.

[139] M. Allen, M. Wigglesworth, Innovation leading the way: Application of lean manufacturing to sample management, J. Biomol. Screen. 14 (5) (2009) 515–522.

[140] R. Andrecioli, Y. Lin, Lean manufacturing and cycle time variability analysis for factory automation using simulation tools, in: 2008 ASME International Mechanical Engineering Congress and Exposition, IMECE 2008, Vol. 4, Boston, MA, 2009, pp. 435–440.

[141] A. Caputo, P. Pelagagge, Parametric and neural methods for cost estimation of process vessels, International Journal of Production Economics 112 (2) (2008) 934–954.

[142] A. Caputo, P. Pelagagge, Effects of product design on assembly lines performances: A concurrent engineering approach, Industrial Management and Data Systems 108 (6) (2008) 726–749.

[143] A. Skoogh, B. Johansson, A methodology for input data management in discrete event simulation projects, in: S. J. Mason, R. R. Hill, L. M′onch, O. Rose, T. Jefferson, J. W. Fowler (Eds.), Proceedings of the 2008 Winter Simulation Conference, 2008, pp. 1727–1735.

[144] J. Hill, S. Onggo, Data identification and collection methodology in a simulation project: an action research, in: B. Tjahjono, C. Heavey, S. Onggo, D.-J. van der Zee (Eds.), Proceedings of the Operational Research Society Simulation Workshop, 2012, pp. 211–220.

[145] T. Perera, K. Liyanage, Methodology for rapid identification and collection of input data in the simulation of manufacturing systems, Simulation Practice and Theory 7 (7) (2000) 645–656.

[146] K. Rampersad, B. Tjahjono, Rapid simulation modelling using cladistics, in: Proceedings of the 8th International Conference on Manufacturing Research ICMR, 2010.

[147] K. Rampersad, B. Tjahjono, An initial classification and compilation of manufacturing systems, in: Proceedings of the Cranfield Multi-Strand Conference, 2008.

[148] D. Borisoglebsky, R. Roy, E. Shehab, A process of information collection for discrete event simulation modelling of production systems, in: The 21st International Computer-Aided Production Engineering Conference, 2010.

[149] D. Borisoglebsky, Development of an activity based cost estimating intelligent e-mentor framework, Master's thesis, Cranfield University (2006).

[150] G. Cokins, Activity-Based Cost Management Making It Work: A Manager's Guide to Implementing and Sustaining an Effective ABC System, McGraw-Hill, 1996.

[151] U. von Beck, J. W. Nowak, The merger of discrete event simulation with activity based costing for cost estimation in manufacturing environments, in: 2000 Winter Simulation Proceedings, Vol. 2, Orlando, FL, USA, 2000, pp. 2048–2054.

[152] C. Robson, Real world research: a resource for social scientists and practitioner-researchers., 2nd Edition, Blackwell Publishing, 2002.

[153] T. Kuhn, The structure of scientific revolutions, 3rd Edition, The University of Chicago Press, 1996.

[154] U. Bititci, V. Martinez, P. Albores, K. Mendibil, Creating and sustaining competitive advantage in collaborative systems: The what and the how, Production Planning and Control 14 (5) (2003) 410–424.

[155] U. Bititci, K. Mendibil, V. Martinez, P. Albores, Measuring and managing performance in extended enterprises, International Journal of Operations and Production Management 25 (4) (2005) 333–353.

[156] E. M. Goldratt, J. Cox, The goal: a process of ongoing improvement, 3rd Edition, The North River Press, 2004.

[157] G. Miller, The magical number seven, plus or minus two: some limits on our capacity for processing information, Psychological Review 63 (2) (1956) 81–97.

[158] J.-C. Pomerol, S. Barba-Romero, Multicriterion Decision in Management: Principles and Practice, Kluwer Academic Publishers, 2000.

[159] H. Gardner, Multiple Intelligences: New Horizons, Basic Books, 2006.

[160] A. C. Alvarez, Modelling and optimisation of corus internal road transportation system, Master's thesis, Cranfield University (2008).

[161] M. A. Fahad, Modelling and optimisation of storage and despatch operations of packed tubes, Master's thesis, Cranfield University (2008).

[162] J. Durillo, A. Nebro, E. Alba, The jmetal framework for multi-objective optimization: Design and architecture, in: CEC 2010, Barcelona, Spain, 2010, pp. 4138–4325.

[163] F. Kursawe, A variant of evolution strategies for vector optimization, in: Parallel Problem Solving from Nature. 1st Workshop, PPSN I, volume 496 of Lecture Notes in Computer Science, Springer-Verlag, 1991, pp. 193–197.

[164] Y. Zhang, J. Fuh, W. Chan, Feature-based cost estimation for packaging products using neural networks, Computers in Industry 32 (1) (1996) 95–113.

[165] A. Shtub, Y. Zimerman, A neural-network-based approach for estimating the cost of assembly systems, International Journal of Production Economics 32 (2) (1993) 189–207.

[166] T. Turner, V. Martinez, U. Bititci, Managing the value delivery process, International Journal of Physical Distribution & Logistics Management 34 (4) (2004) 333–353.

[167] L. Zheng, C. McMahon, L. Li, L. Ding, J. Jamshidi, Key characteristics management in product lifecycle management: A survey of methodologies and practices, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 222 (8) (2008) 989–1008.

[168] Y. Asiedu, P. Gu, Product life cycle cost analysis: State of the art review, International Journal of Production Research 36 (4) (1998) 883–908.

[169] F. Jovane, L. Alting, A. Armillotta, W. Eversheim, K. Feldmann, G. Seliger, N. Roth, A key issue in product life cycle: Disassembly, CIRP Annals - Manufacturing Technology 42 (2) (1993) 651–658.

[170] J. Park, T. Simpson, Toward an activity-based costing system for product families and product platforms in the early stages of development, International Journal of Production Research 46 (1) (2008) 99–130.

[171] E. Kirche, R. Srivastava, An abc-based cost model with inventory and order level costs: A comparison with toc, International Journal of Production Research 43 (8) (2005) 1685–1710.

[172] E. Brinke, E. Lutters, T. Streppel, H. Kals, Cost estimation architecture for integrated cost control based on information management, International Journal of Computer Integrated Manufacturing 17 (6) (2004) 534–545.

[173] M. Johnson, R. Kirchain, Quantifying the effects of parts consolidation and development costs on material selection decisions: A process-based costing approach, International Journal of Production Economics 119 (1) (2009) 174–186.

[174] Y. Tu, S. Xie, R. Fung, Product development cost estimation in mass customization, IEEE Transactions on Engineering Management 54 (1) (2007) 29–40.

[175] K. Bauer, Costing for castings, Modern Casting 95 (6) (2005) 33–36.

[176] B. Hicks, S. Culley, G. Mullineux, Cost estimation for standard components and systems in the early phases of the design process, Journal of Engineering Design 13 (4) (2002) 271–292.

[177] E. Ten Brinke, E. Lutters, T. Streppel, H. Kals, Variant-based cost estimation based on information management, International Journal of Production Research 38 (17 SPEC.) (2000) 4467–4479.

[178] K. Schreve, H. Schuster, A. Basson, Manufacturing cost estimation during design of fabricated parts, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 213 (7) (1999) 731–735.

[179] R. Roy, S. Colmer, T. Griggs, Estimating the cost of a new technology intensive automotive product: A case study approach, International Journal of Production Economics 97 (2) (2005) 210–226.

[180] D. Ben-Arieh, Q. Li, Web-based cost estimation of machining rotational parts, Production Planning and Control 14 (8) (2003) 778–788.

[181] B. Verlinden, J. Duflou, P. Collin, D. Cattrysse, Cost estimation for sheet metal parts using multiple regression and artificial neural networks: A case study, International Journal of Production Economics 111 (2) (2008) 484–492.

[182] R. Chougule, B. Ravi, Casting cost estimation in an integrated product and process design environment, International Journal of Computer Integrated Manufacturing 19 (7) (2006) 676–688.

[183] B. Bidanda, M. Kadidal, R. Billo, Development of an intelligent castability and cost estimation system, International Journal of Production Research 36 (2) (1998) 547–568.

[184] T. Farineau, B. Rabenasolo, J. Castelain, Y. Meyer, P. Duverlie, Use of parametric models in an economic evaluation step during the design phase, International Journal of Advanced Manufacturing Technology 17 (2) (2001) 79–86.

[185] Z.-C. Lin, D.-Y. Chang, Cost-tolerance analysis model based on a neural networks method, International Journal of Production Research 40 (6) (2002) 1429–1452.

[186] Nagahanumaiah, N. Mukherjee, B. Ravi, An integrated framework for die and mold cost estimation using design features and tooling parameters, International Journal of Advanced Manufacturing Technology 26 (9-10) (2005) 1138–1149.

[187] J. Ciurana, G. Quintana, M. Garcia-Romeu, Estimating the cost of vertical high-speed machining centres, a comparison between multiple regression analysis and the neural networks approach, International Journal of Production Economics 115 (1) (2008) 171–178.

[188] J. de Cos, F. Sanchez, F. Ortega, V. Montequin, Rapid cost estimation of metallic components for the aerospace industry, International Journal of Production Economics 112 (1) (2008) 470–482.

[189] J. Bode, Neural networks for cost estimation: Simulations and pilot application, International Journal of Production Research 38 (6) (2000) 1231–1254.

[190] A. Shtub, R. Versano, Estimating the cost of steel pipe bending, a comparison between neural networks and regression analysis, International Journal of Production Economics 62 (3) (1999) 201–207.

[191] Z. Wang, W. Knight, Economic evaluation of design-for-test alternatives for microelectronics products, CIRP Annals - Manufacturing Technology 51 (1) (2002) 123–126.

[192] Z. Wang, W. Knight, Economic impacts during microelectronics product design, CIRP Annals - Manufacturing Technology 50 (1) (2001) 97–100.

[193] K. Shimohashi, X. Zhou, J. Schoenung, A test-rework process yield performance model for estimation of printed wiring board assembly cost, International Journal of Production Economics 119 (1) (2009) 161–173.

[194] D. Miller, Determining the cost of welding, Welding Design and Fabrication 77 (3) (2004) –.

[195] S. Kumar, G. Chattopadhyay, U. Kumar, Reliability improvement through alternative designs-a case study, Reliability Engineering and System Safety 92 (7) (2007) 983–991.

[196] T. Smunt, Log-linear and non-log-linear learning curve models for production research and cost estimation, International Journal of Production Research 37 (17) (1999) 3901–3911.

[197] K.-K. Seo, B. Ahn, A learning algorithm based estimation method for maintenance cost of product concepts, Computers and Industrial Engineering 50 (1-2) (2006) 66–75.

[198] O. Duran, N. Rodriguez, L. Consalter, Neural networks for cost estimation of shell and tube heat exchangers, Expert Systems with Applications 36 (4) (2009) 7435–7440.

[199] M. Ikeda, T. Hiyama, Ann based designing and cost determination system for induction motor, IEE Proceedings: Electric Power Applications 152 (6) (2005) 1595–1602.

[200] H. Wang, X. Zhou, X.-Y. Ruan, Research on injection mould intelligent cost estimation system and key technologies, International Journal of Advanced Manufacturing Technology 21 (3) (2003) 215–222.

[201] T. Spedding, G. Sun, Application of discrete event simulation to the activity based costing of manufacturing systems, International Journal of Production Economics 58 (3) (1999) 289–301.

[202] D. Kiritsis, K.-P. Neuendorf, P. Xirouchakis, Petri net techniques for process planning cost estimation, Advances in Engineering Software 30 (6) (1999) 375–387.

[203] P. Xirouchakis, D. Kiritsis, C. Gunther, J.-G. Persson, Petri net technique for batch delivery time estimation, CIRP Ann Manuf Technol 48 (1) (1999) 361–364.

[204] Y. Asiedu, R. Besant, P. Gu, Simulation-based cost estimation under economic uncertainty using kernel estimators, International Journal of Production Research 38 (9) (2000) 2023–2035.

[205] I.-T. Yang, Distribution-free monte carlo simulation: Premise and refinement, Journal of Construction Engineering and Management 134 (5) (2008) 352–360.

[206] T. Sastri, B. Feiring, P. Mongkolwana, Markov chain approach to failure cost estimation in batch manufacturing, Quality Engineering 13 (1) (2000) 43–49.

[207] J. Gilbert, I. Bell, D. Johnson, Circuit design optimization based on quality cost estimation, Quality and Reliability Engineering International 21 (4) (2005) 367–386.

[208] J. Wrobel, M. Laudański, Cost assessment in design of low volume manufacture machines, Automation in Construction 17 (3) (2008) 265–270.

[209] F. Elgh, M. Cederfeldt, Cost-based producibility assessment: Analysis and synthesis approaches through design automation, Journal of Engineering Design 19 (2) (2008) 113–130.

[210] Z. Bouaziz, J. Younes, A. Zghal, Cost estimation system of dies manufacturing based on the complex machining features, International Journal of Advanced Manufacturing Technology 28 (3-4) (2006) 262–271.

[211] E. Shehab, H. Abdalla, A cost-effective knowledge-based reasoning system for design for automation, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 220 (5) (2006) 729–743.

[212] A. Kamrani, A. Vijayan, A methodology for integrated product development using design and manufacturing templates, Journal of Manufacturing Technology Management 17 (5) (2006) 656–672.

[213] Z. Zhao, J. Shah, Domain independent shell for dfm and its application to sheet metal forming and injection molding, Computer-Aided Design 37 (9) (2005) 881–898.

[214] D. Koonce, R. Judd, D. Sormaz, D. Masel, A hierarchical cost estimation tool, Computers in Industry 50 (3) (2003) 293–302.

[215] S. Gupta, Y. Chen, S. Feng, R. Sriram, A system for generating process and material selection advice during embodiment design of mechanical components, Journal of Manufacturing Systems 22 (1) (2003) 28–45.

[216] E. Shehab, H. Abdalla, An intelligent knowledge-based system for product cost modelling, International Journal of Advanced Manufacturing Technology 19 (1) (2002) 49–65.

[217] E. Shehab, H. Abdalla, A design to cost system for innovative product development, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 216 (7) (2002) 999–1019.

[218] E. Shehab, H. Abdalla, Manufacturing cost modelling for concurrent product development, Robotics and Computer-Integrated Manufacturing 17 (4) (2001) 341–353.

[219] Y. Wei, P. Egbelu, A framework for estimating manufacturing cost from geometric design data, International Journal of Computer Integrated Manufacturing 13 (1) (2000) 50–63.

[220] A. Gayretli, H. Abdalla, Object-oriented constraints-based system for concurrent product development, Robotics and Computer-Integrated Manufacturing 15 (2) (1999) 133–144.

[221] A. Gayretli, H. Abdalla, A prototype constraint-based system for the automation and optimization of machining processes, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 213 (7) (1999) 655–676.

[222] J. Jiao, M. Tseng, A pragmatic approach to product costing based on standard time estimation, International Journal of Operations and Production Management 19 (7) (1999) 738–755.

[223] T. Geiger, D. Dilts, Automated design-to-cost: Integrating costing into the design decision, Computer-Aided Design 28 (6-7) (1996) 423–438.

[224] A. Van Der Laan, M. Van Tooren, Incorporating cost analysis in a multi-disciplinary design environment for aircraft movables, Journal of Engineering Design 19 (2) (2008) 131–144.

[225] F. H'mida, P. Martin, F. Vernadat, Cost estimation in mechanical production: The cost entity approach applied to integrated product engineering, International Journal of Production Economics 103 (1) (2006) 17–35.

[226] H. Wang, Application of bpn with feature-based models on cost estimation of plastic injection products, Computers and Industrial Engineering 53 (1) (2007) 79–94.

[227] W. Yan, C.-H. Chen, L. Khoo, M. Pritchard, A strategy for integrating product conceptualization and bid preparation, International Journal of Advanced Manufacturing Technology 29 (5) (2006) 616–628.

[228] M. Mauchand, A. Siadat, A. Bernard, N. Perry, Proposal for tool-based method of product cost estimation during conceptual design, Journal of Engineering Design 19 (2) (2008) 159–172.

[229] H. Jahan-Shahi, E. Shayan, S. Masood, Cost estimation in flat plate processing using fuzzy sets, Computers and Industrial Engineering 37 (1) (1999) 485–488.

[230] T. Koltai, S. Lozano, F. Guerrero, L. Onieva, A flexible costing system for flexible manufacturing systems using activity based costing, International Journal of Production Research 38 (7) (2000) 1615–1630.

[231] Y.-T. Tsai, Y.-M. Chang, Function-based cost estimation integrating quality function deployment to support system design, International Journal of Advanced Manufacturing Technology 23 (7-8) (2004) 514–522.

[232] S. de la Maza, A knowledge capture methodology for developing a supply chain simulation within the steel making industry, Master's thesis, Cranfield University (2004).

[233] Integration definition for function modeling (idef0)., (accessed 10th February 2011) (02 2011), http://www.idef.com/pdf/idef0.pdf.

Appendix A

Simulation modelling projects

BU	Area	Objective
RD&T	Bloom & Billet Mill Scunthorpe	Access grinding capacities
RD&T	Brinsworth Annealing	Improve scheduling with new products
RD&T	Llanwern finishing end	Remove finishing end conjesting & explore lean practices (planning)
RD&T	Scunthorp Steel Plan. & Casting (Feasibility)	Feasibility for model to determine capacity with new configuration
RD&T	CSPUK (Strip) PT & Llanwern transport infrastructure	Design Rail & Road operations to handle 20% increase in Production
RD&T	CSPUK (Strip) PT	Determine if more locos needed (or HM supply to steel plant)
RD&T	CES Restructuring casting & outbound logistics from Casting	Operations design
RD&T	CES Restructuring slow cooling facilities	design - how many - general knowledge development
RD&T	CES Restructuring Aldwarke Primary Mill Design	New mill modelling before construction
RD&T	CES Restructuring Aldwarke Primary Mill Saws	Model capability of saws & bottleneck impact
RD&T	CES Restructuring Aldwarke Primary Mill delays & scheduling	Heaving facility & possibility of use in conjunction with scheduling
RD&T	CES Scrap Handling Scheme	Design of scheme to making maximum planned capacity of steel plant
RD&T	CES Stocksbridge Finishing Ops	How much material can potentially be produced
RD&T	Shotton supply chain planning (manufacturing)	Design templates investigation manufacturing impact of differing campaign plans
RD&T	Panels & Proiles Ammanferd	Design of a panels cell / line
RD&T	Ijmuiden Supply Chain Planning (SEGAL)	Understand & influence flow of material firm Ijmuiden to Segal
RD&T	Lean training simulation	Investigate impact of push vs pull operation strategy for simple manufacturing layout
RD&T	Scunthorpe Heavy Plate Mill	First strategic innovation. Explore possibility to optimise scheduling for reheat furnace and rolling mill
RD&T	Shotton Rail Head	Design of railhead feeding the Galv lines at Shotton
Trostre	Trostre 2week leadtime	Capability of Kanban operation of Trostre Process
Teesside	Teesside cast Products Steel Plant	
Port Talbot	Port Talbot Steel Plant	Balance of steelmaking and casting

Appendix B

Case study 1 in Chapter 6

Week	1	2	3	4	5	6	7	8	9	10	11	12	13
CTL	0.238	0.379	0.398	0.582	0.243	0.397	0.241	0.483	0.185	0.347	0.256	0.565	0.213
Gr	0.197	0.467	0.468	0.730	0.201	0.511	0.214	0.591	0.119	0.422	0.252	0.703	0.161

Week	14	15	16	17	18	19	20	21	22	23	24	25	26
CTL	0.421	0.126	0.374	0.559	0.343	0.559	0.619	0.274	0.589	0.320	0.644	0.403	0.643
Gr	0.537	0.045	0.428	0.732	0.361	0.732	0.818	0.287	0.796	0.345	0.852	0.499	0.843

Week	27	28	29	30	31	32	33	34	35	36	37	38	39
CTL	0.439	0.717	0.444	0.670	0.097	0.097	0.612	0.409	0.323	0.621	0.421	0.622	0.335
Gr	0.541	0.986	0.553	0.879	0.000	0.000	0.827	0.458	0.359	0.811	0.526	0.784	0.367

Week	40	41	42	43	44	45	46	47	48	49	50	51	52
CTL	0.618	0.340	0.340	0.631	0.367	0.795	0.444	0.464	0.369	0.030	0.027	0.023	0.022
Gr	0.833	0.390	0.390	0.821	0.429	1.117	0.548	0.540	0.432	0.006	0.003	0.001	0.000

Table B.1: Utlisation of resource in Cut To Length (CTL) and Grooving (Gr) machines, 52 weeks year 2007.

Week	1	2	3	4	5	6	7	8	9	10	11	12	13
PF1	325.00	325.00	325.00	325.00	325.00	325.00	325.00	325.00	325.00	325.00	325.00	325.00	325.00
PF2	140.25	235.58	266.52	411.83	144.75	257.53	133.99	340.10	89.03	218.25	140.44	391.71	122.11
PF3	140.25	235.58	266.52	411.83	144.75	257.53	133.99	340.10	89.03	218.25	140.44	391.71	122.11
Total	605.51	796.16	858.03	1148.67	614.50	840.06	592.97	1005.19	503.06	761.49	605.88	1108.42	569.22

Week	14	15	16	17	18	19	20	21	22	23	24	25	26
PF1	325.00	325.00	325.00	325.00	325.00	325.00	325.00	325.00	325.00	325.00	325.00	325.00	325.00
PF2	272.22	25.34	256.33	425.69	227.65	425.69	405.32	167.67	444.25	219.08	420.15	277.68	501.28
PF3	272.22	25.34	256.33	425.69	227.65	425.69	405.32	167.67	444.25	219.08	420.15	277.68	501.28
Total	869.43	375.67	837.66	1176.38	780.30	1176.38	1135.63	660.34	1213.49	763.16	1165.31	880.37	1327.55

Week	27	28	29	30	31	32	33	34	35	36	37	38	39
PF1	325.00	325.00	325.00	325.00	325.00	325.00	325.00	325.00	325.00	325.00	325.00	325.00	325.00
PF2	340.09	461.15	340.42	522.46	0.00	0.00	473.72	244.65	229.82	514.27	296.09	396.79	241.37
PF3	340.09	461.15	340.42	522.46	0.00	0.00	473.72	244.65	229.82	514.27	296.09	396.79	241.37
Total	1005.18	1247.30	1005.84	1369.93	325.00	325.00	1272.45	814.30	784.64	1353.54	917.17	1118.58	807.74

Week	40	41	42	43	44	45	46	47	48	49	50	51	52
PF1	325.00	325.00	325.00	325.00	325.00	325.00	325.00	325.00	325.00	325.00	325.00	325.00	325.00
PF2	457.72	234.67	234.67	407.28	248.23	586.50	345.28	292.62	261.91	489.22	263.90	121.21	12.88
PF3	457.72	234.67	234.67	407.28	248.23	707.54	345.28	292.62	261.91	489.22	263.90	121.21	12.88
Total	1240.45	794.33	794.33	1139.56	821.45	1619.05	1015.55	910.24	848.82	1303.43	852.80	567.41	350.76

Table B.2: Throughput in tonnes per product family (PF), data for 52 weeks, year 2007.

Week	1	2	3	4	5	6	7	8	9	10	11	12	13
PF1	0.238	0.379	0.398	0.582	0.243	0.397	0.241	0.483	0.185	0.347	0.256	0.565	0.213
PF2	0.436	0.846	0.865	1.312	0.444	0.908	0.454	1.075	0.304	0.770	0.508	1.268	0.375
PF3	0.197	0.467	0.468	0.730	0.201	0.511	0.214	0.591	0.119	0.422	0.252	0.703	0.161
Total	0.871	1.691	1.730	2.624	0.888	1.815	0.908	2.149	0.608	1.540	1.017	2.536	0.749

Week	14	15	16	17	18	19	20	21	22	23	24	25	26
PF1	0.421	0.126	0.374	0.559	0.343	0.559	0.619	0.274	0.589	0.320	0.644	0.403	0.643
PF2	0.958	0.172	0.802	1.292	0.704	1.292	1.437	0.561	1.385	0.665	1.496	0.902	1.486
PF3	0.537	0.045	0.428	0.732	0.361	0.732	0.818	0.287	0.796	0.345	0.852	0.499	0.843
Total	1.915	0.343	1.604	2.583	1.408	2.583	2.874	1.122	2.770	1.330	2.993	1.804	2.972

Week	27	28	29	30	31	32	33	34	35	36	37	38	39
PF1	0.439	0.717	0.444	0.670	0.097	0.097	0.612	0.409	0.323	0.621	0.421	0.622	0.335
PF2	0.980	1.702	0.996	1.549	0.097	0.097	1.439	0.867	0.682	1.431	0.948	1.406	0.702
PF3	0.541	0.986	0.553	0.879	0.000	0.000	0.827	0.458	0.359	0.811	0.526	0.784	0.367
Total	1.961	3.405	1.993	3.098	0.193	0.193	2.877	1.735	1.364	2.863	1.895	2.813	1.404

Week	40	41	42	43	44	45	46	47	48	49	50	51	52
PF1	0.618	0.340	0.340	0.631	0.367	0.795	0.444	0.464	0.369	0.030	0.027	0.023	0.022
PF2	1.451	0.730	0.730	1.452	0.796	1.912	0.992	1.004	0.801	0.036	0.030	0.025	0.022
PF3	0.833	0.390	0.390	0.821	0.429	1.117	0.548	0.540	0.432	0.006	0.003	0.001	0.000
Total	2.901	1.460	1.460	2.905	1.592	3.824	1.983	2.009	1.602	0.073	0.060	0.050	0.043

Table B.3: Matrix Y: Part of the resource consumption per product family, data for 52 weeks, year 2007.

Week	1	2	3	4	5	6	7	8	9	10	11	12	13
PF1	88.85	72.77	74.68	72.12	88.85	71.02	86.09	73.10	98.93	73.33	81.92	72.36	92.61
PF2	70.13	117.79	133.26	205.92	72.37	128.77	66.99	170.05	44.51	109.12	70.22	195.86	61.06
PF3	31.79	65.04	72.02	114.52	32.80	72.49	31.50	93.55	17.41	59.88	34.82	108.64	26.26
Total	190.76	255.60	279.96	392.56	194.03	272.27	184.58	336.70	160.86	242.33	186.96	376.86	179.93

Week	14	15	16	17	18	19	20	21	22	23	24	25	26
PF1	71.43	119.45	75.77	70.38	79.25	70.38	70.03	79.35	69.09	78.30	69.94	72.55	70.32
PF2	136.11	12.67	128.16	212.85	113.83	212.85	202.66	83.84	222.12	109.54	210.08	138.84	250.64
PF3	76.28	3.36	68.40	120.66	58.32	120.66	115.32	42.90	127.68	56.76	119.66	76.86	142.18
Total	283.82	135.48	272.34	403.88	251.39	403.88	388.01	206.08	418.89	244.60	399.68	288.25	463.14

Week	27	28	29	30	31	32	33	34	35	36	37	38	39
PF1	72.77	68.39	72.34	70.24	162.50	162.50	69.13	76.66	76.97	70.49	72.27	71.92	77.55
PF2	170.05	230.57	170.21	261.23	0.00	0.00	236.86	122.33	114.91	257.14	148.04	198.40	120.68
PF3	93.90	133.53	94.44	148.32	0.00	0.00	136.10	64.62	60.48	145.60	82.21	110.58	63.09
Total	336.71	432.50	336.99	479.79	162.50	162.50	442.09	263.60	252.36	473.22	302.51	380.90	261.32

Week	40	41	42	43	44	45	46	47	48	49	50	51	52
PF1	69.19	75.79	75.79	70.63	75.00	67.57	72.70	75.11	74.85	134.77	144.36	153.05	161.60
PF2	228.86	117.33	117.33	203.64	124.11	293.25	172.64	146.31	130.95	244.61	131.95	60.60	6.44
PF3	131.42	62.61	62.61	115.13	66.83	206.68	95.40	78.69	70.64	41.74	14.73	3.52	0.04
Total	429.47	255.73	255.73	389.40	265.94	567.49	340.74	300.10	276.44	421.12	291.04	217.18	168.08

Table B.4: Matrix Z: Part of the resource consumption per product family considering its throughput, data for 52 weeks, year 2007.

Week	1	2	3	4	5	6	7	8	9	10	
PF1	28201.76	22668.07	22889.17	21103.78	28140.16	21911.76	27656.52	21823.91	30938.68	23041.89	
PF2	22259.84	36689.83	40842.31	60252.51	22921.47	39728.67	21521.16	50766.52	13921.19	34290.33	
PF3	10089.30	20258.48	22071.97	33510.27	10388.31	22365.73	10119.40	27928.88	5445.97	18817.07	
Total	60550.90	79616.38	85803.46	114866.56	61449.94	84006.16	59297.08	100519.30	50305.84	76149.28	

Week	11	12	13	14	15	16	17	18	19	20	
PF1	26546.89	21283.54	29298.74	21881.74	33123.81	23306.50	20500.37	24598.31	20500.37	20495.74	
PF2	22756.09	57605.59	19315.94	41694.72	3512.89	39420.54	61994.68	35331.25	61994.68	59314.02	
PF3	11284.70	31953.23	8307.60	23366.82	930.61	21038.64	35142.97	18100.90	35142.97	33753.30	
Total	60587.68	110842.36	56922.28	86943.28	37567.30	83765.68	117638.02	78030.46	117638.02	113563.06	

Week	21	22	23	24	25	26	27	28	29	30	
PF1	25425.28	20015.83	24431.18	20392.11	22157.44	20156.20	21723.72	19724.17	21591.19	20054.80	
PF2	26863.20	64346.65	34176.57	61250.64	42405.34	71843.76	50763.63	66496.35	50804.40	74588.88	
PF3	13745.94	36986.78	17707.85	34888.09	23473.82	40755.12	28031.11	38509.32	28188.69	42349.14	
Total	66034.42	121349.26	76315.60	116530.84	88036.60	132755.08	100518.46	124729.84	100584.28	136992.82	

Week	31	32	33	34	35	36	37	38	39	40	41
PF1	32500.00	32500.00	19896.91	23680.80	23930.35	20160.81	21909.61	21121.42	23970.51	19984.03	23540.27
PF2	0.00	0.00	68175.01	37788.02	35727.75	73547.82	44883.86	58261.96	37302.64	66103.01	36445.20
PF3	0.00	0.00	39172.99	19961.67	18805.74	41645.84	24923.53	32474.90	19500.44	37957.84	19447.91
Total	32500.00	32500.00	127244.92	81430.48	78463.84	135354.46	91717.00	111858.28	80773.60	124044.88	79433.38

Week	42	43	44	45	46	47	48	49	50	51	52
PF1	23540.27	20669.46	23166.95	19276.55	21668.00	22780.76	22981.59	41714.34	42299.99	39987.23	33724.78
PF2	36445.20	59594.48	38336.26	83664.04	51453.47	44377.37	40210.28	75710.16	38663.47	15833.29	1344.18
PF3	19447.91	33692.13	20641.99	58964.03	28433.67	23866.17	21689.99	12918.51	4316.14	920.50	7.44
Total	79433.38	113956.06	82145.20	161904.62	101555.14	91024.30	84881.86	130343.02	85279.60	56741.02	35076.40

Table B.5: Matrix S: Overall relative costs per product family, data for 52 weeks, year 2007.

Week	1	2	3	4	5	6	7	8	9	10	11	12	13
PF1	86.8	69.7	70.4	64.9	86.6	67.4	85.1	67.2	95.2	70.9	81.7	65.5	90.1
PF2	158.7	155.7	153.2	146.3	158.4	154.3	160.6	149.3	156.4	157.1	162.0	147.1	158.2
PF3	71.9	86.0	82.8	81.4	71.8	86.8	75.5	82.1	61.2	86.2	80.4	81.6	68.0

Week	14	15	16	17	18	19	20	21	22	23	24	25	26
PF1	67.3	101.9	71.7	63.1	75.7	63.1	63.1	78.2	61.6	75.2	62.7	68.2	62.0
PF2	153.2	138.6	153.8	145.6	155.2	145.6	146.3	160.2	144.8	156.0	145.8	152.7	143.3
PF3	85.8	36.7	82.1	82.6	79.5	82.6	83.3	82.0	83.3	80.8	83.0	84.5	81.3

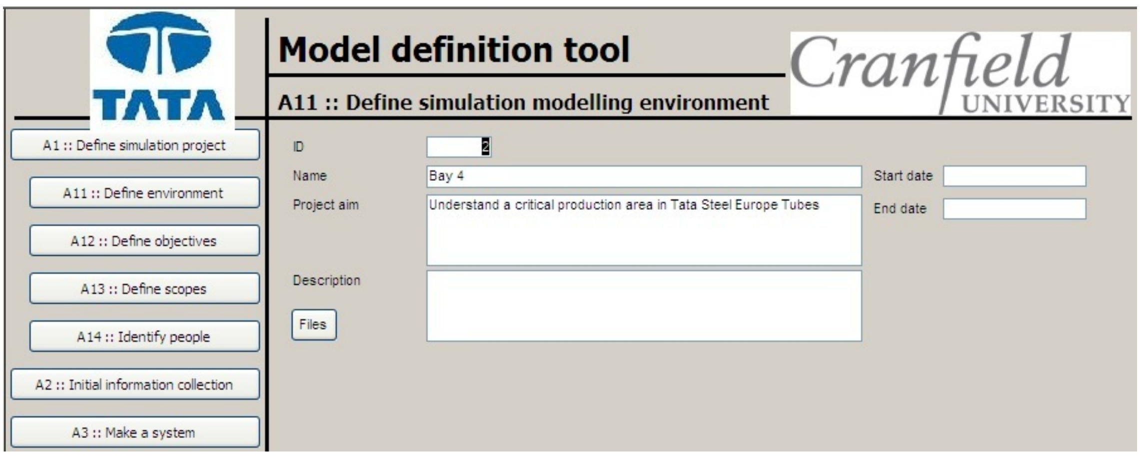
Week	27	28	29	30	31	32	33	34	35	36	37	38	39
PF1	66.8	60.7	66.4	61.7	100.0	100.0	61.2	72.9	73.6	62.0	67.4	65.0	73.8
PF2	149.3	144.2	149.2	142.8	0.0	0.0	143.9	154.5	155.5	143.0	151.6	146.8	154.5
PF3	82.4	83.5	82.8	81.1	0.0	0.0	82.7	81.6	81.8	81.0	84.2	81.8	80.8

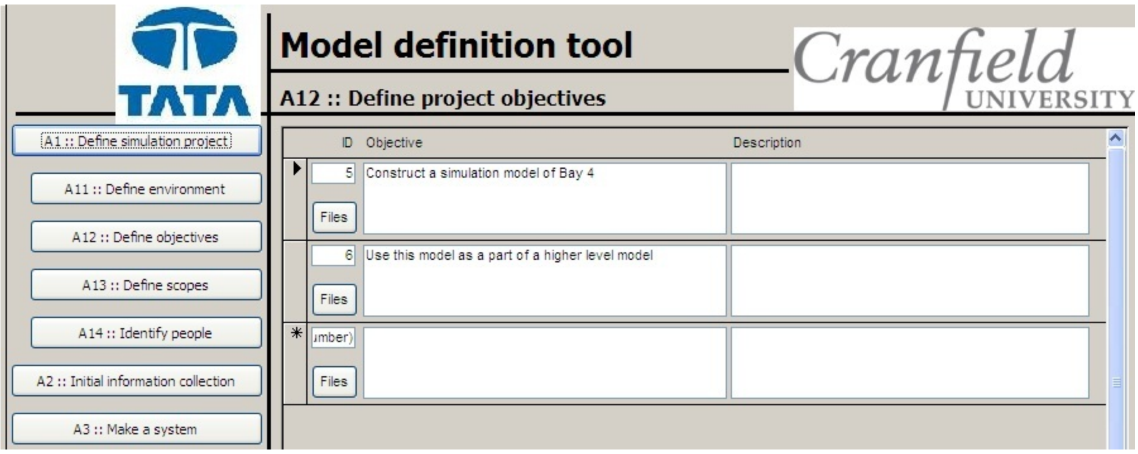
Week	40	41	42	43	44	45	46	47	48	49	50	51	52
PF1	61.5	72.4	72.4	63.6	71.3	59.3	66.7	70.1	70.7	128.4	130.2	123.0	103.8
PF2	144.4	155.3	155.3	146.3	154.4	142.6	149.0	151.7	153.5	154.8	146.5	130.6	104.3
PF3	82.9	82.9	82.9	82.7	83.2	83.3	82.4	81.6	82.8	26.4	16.4	7.6	0.6

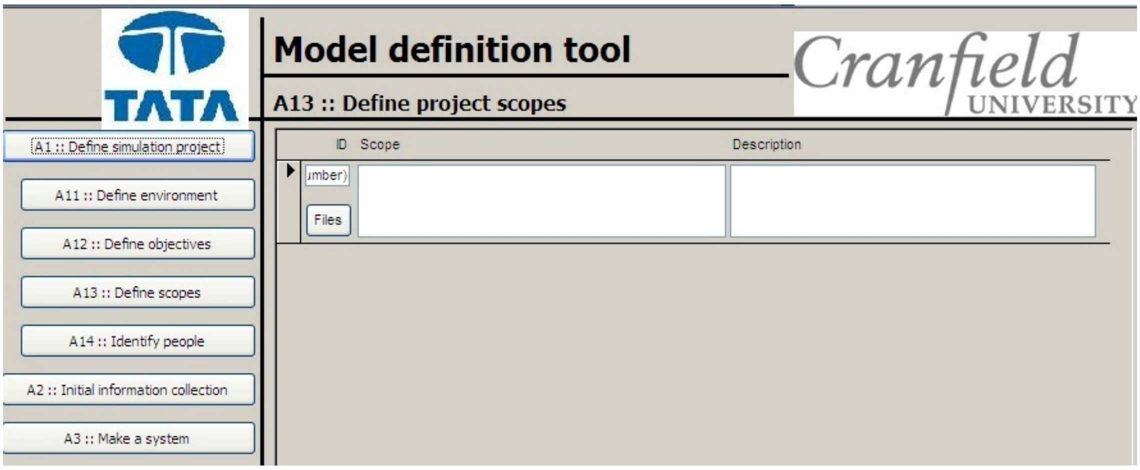
Table B.6: Matrix V: Relative costs per tonne for each product family, data for 52 weeks, year 2007.

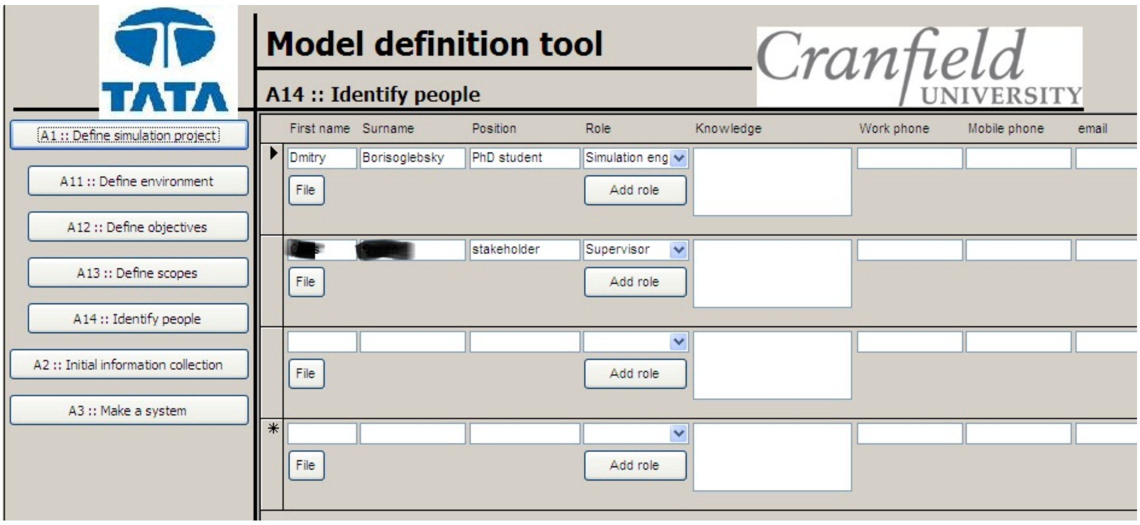
Appendix C

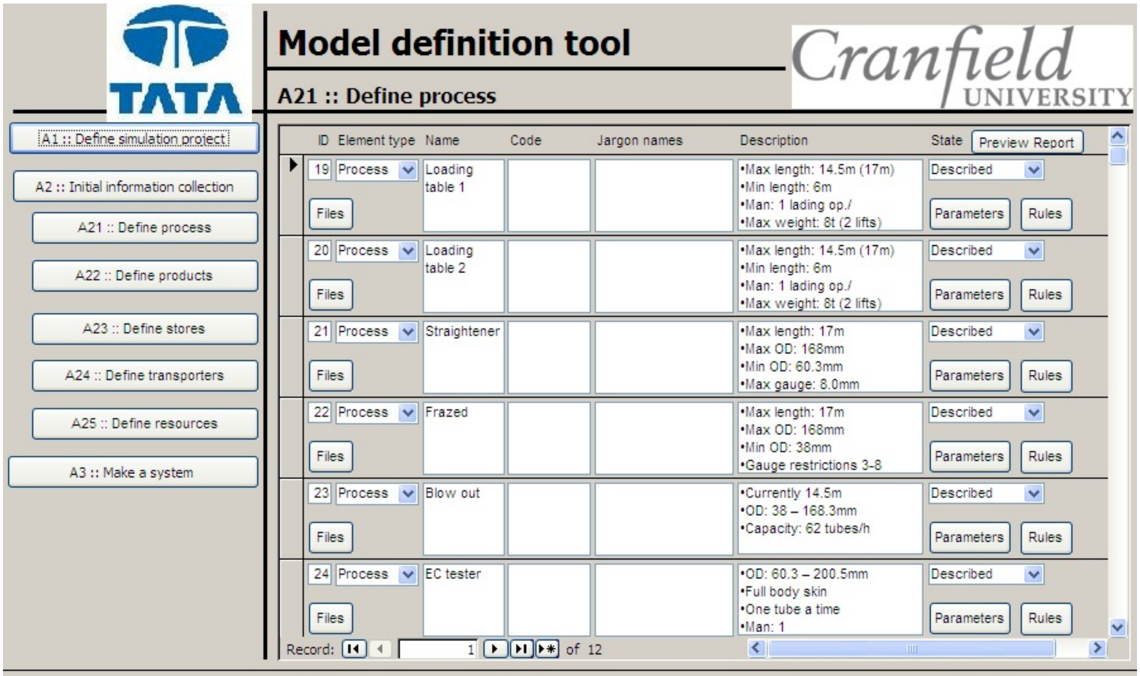
Information collection tool

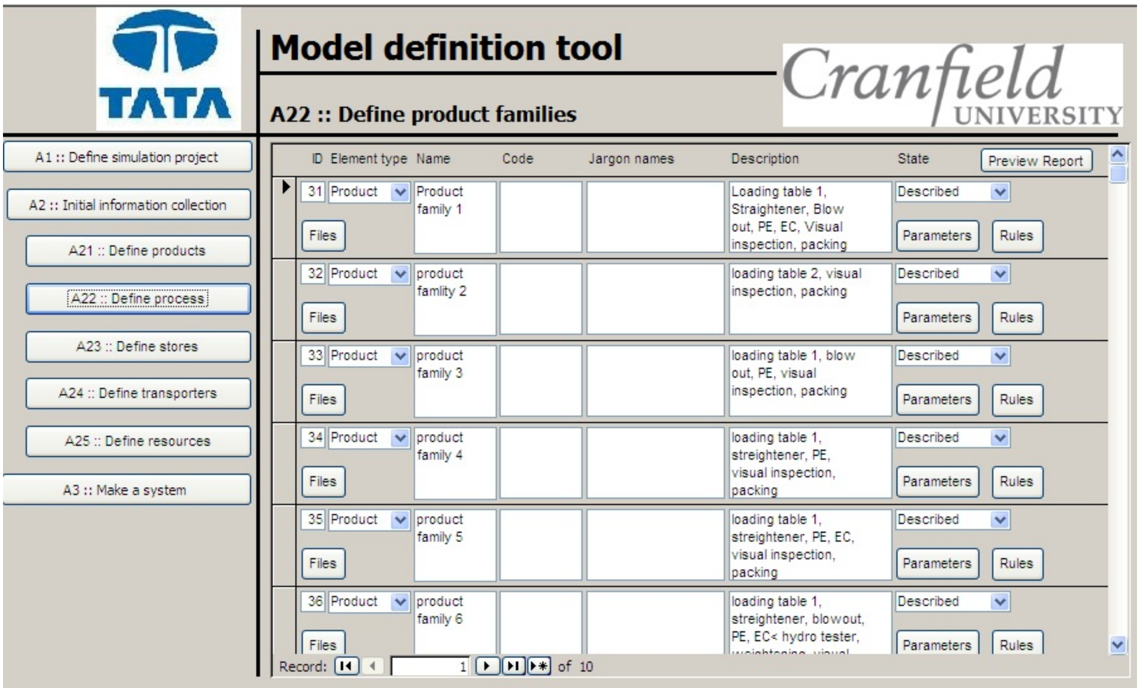


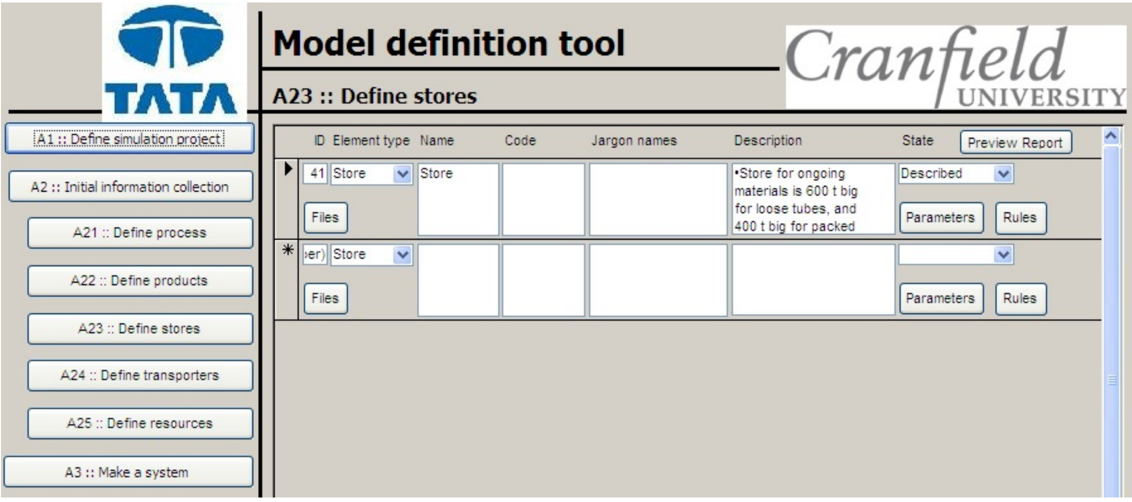

TATA
Model definition tool
Cranfield UNIVERSITY
A12 :: Define project objectives
A1 :: Define simulation project
A11 :: Define environment
A12 :: Define objectives
A13 :: Define scopes
A14 :: Identify people
A2 :: Initial information collection
A3 :: Make a system
ID
Objective
Description
5
Construct a simulation model of Bay 4
Files
6
Use this model as a part of a higher level model
Files
ımber)
Files

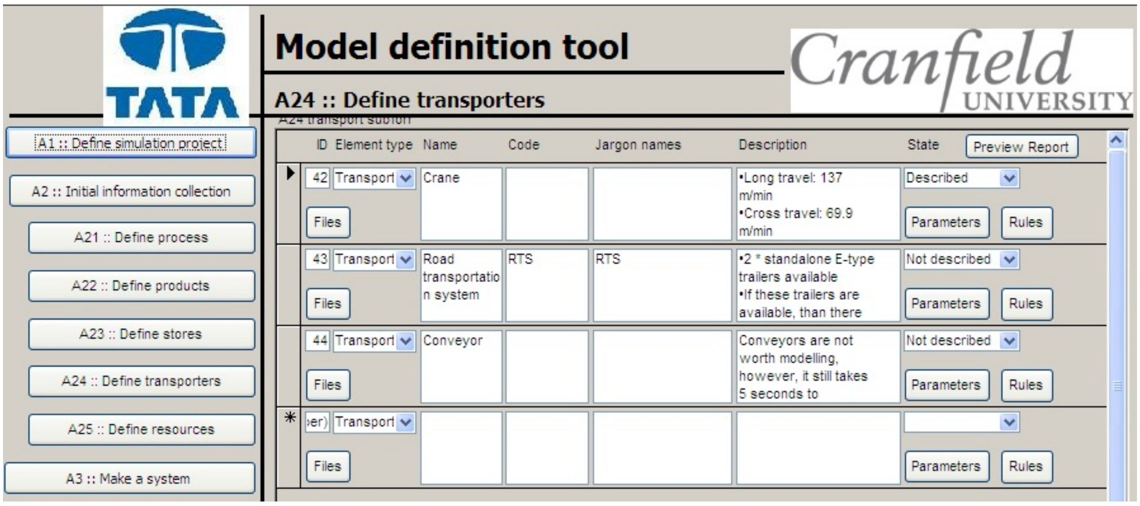

TATA
Model definition tool
Cranfield UNIVERSITY
A13 :: Define project scopes
A1 :: Define simulation project
A11 :: Define environment
A12 :: Define objectives
A13 :: Define scopes
A14 :: Identify people
A2 :: Initial information collection
A3 :: Make a system
ID
Scope
Description
ımber)
Files

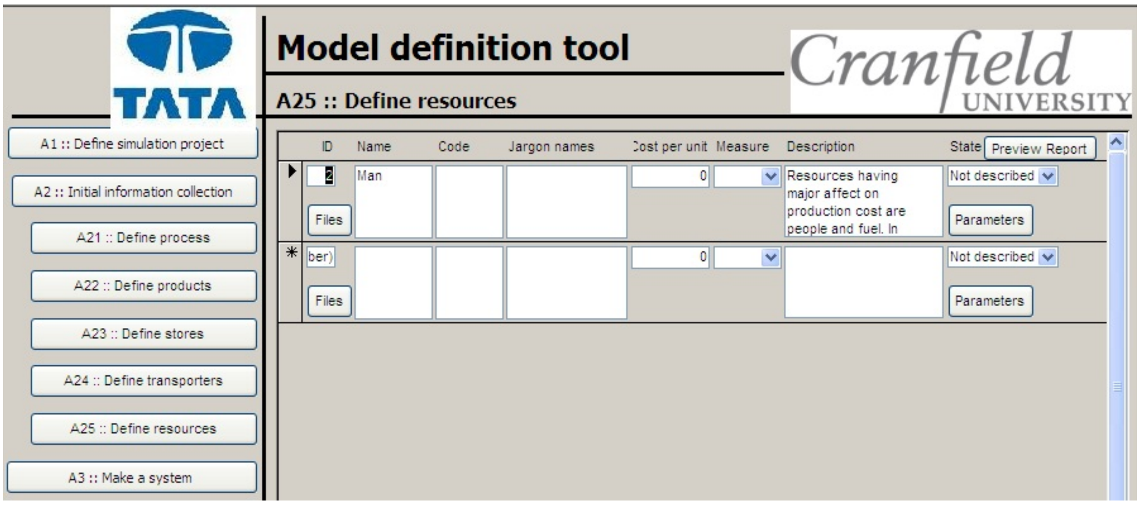

TATA
Model definition tool
Cranfield UNIVERSITY
A14 :: Identify people
A1 :: Define simulation project
A11 :: Define environment
A12 :: Define objectives
A13 :: Define scopes
A14 :: Identify people
A2 :: Initial information collection
A3 :: Make a system
First name
Surname
Position
Role
Knowledge
Work phone
Mobile phone
email
Dmitry
Borisoglebsky
PhD student
Simulation eng
File
Add role
[redacted]
stakeholder
Supervisor
File
Add role
File
Add role
File
Add role

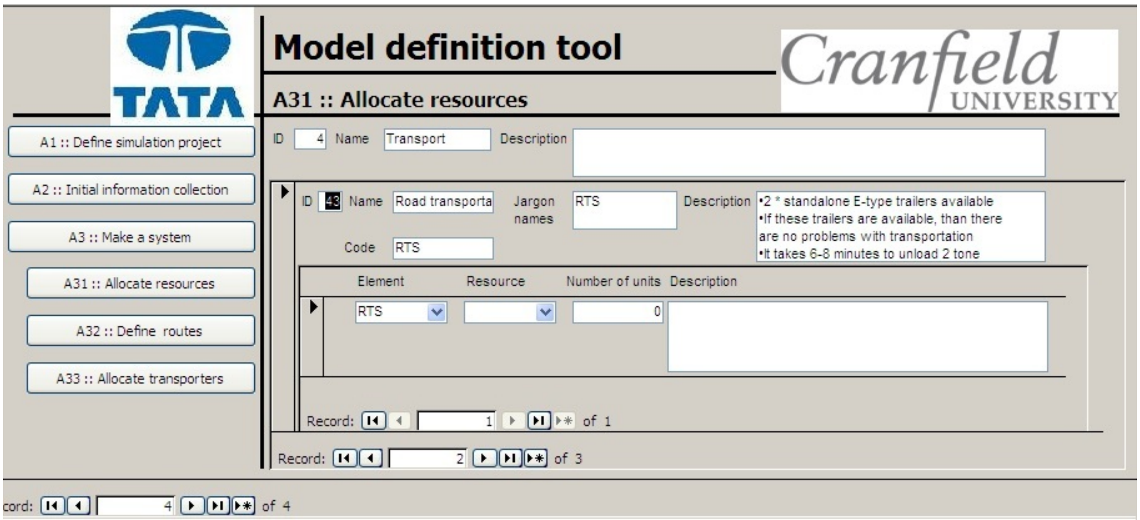

TATA
Model definition tool
Cranfield UNIVERSITY
A21 :: Define process
A1 :: Define simulation project
A2 :: Initial information collection
A21 :: Define process
A22 :: Define products
A23 :: Define stores
A24 :: Define transporters
A25 :: Define resources
A3 :: Make a system
ID Element type Name Code Jargon names Description State Preview Report
19 Process Loading table 1 •Max length: 14.5m (17m) •Min length: 6m •Man: 1 lading op./ •Max weight: 8t (2 lifts) Described
20 Process Loading table 2 •Max length: 14.5m (17m) •Min length: 6m •Man: 1 lading op./ •Max weight: 8t (2 lifts) Described
21 Process Straightener •Max length: 17m •Max OD: 168mm •Min OD: 60.3mm •Max gauge: 8.0mm Described
22 Process Frazed •Max length: 17m •Max OD: 168mm •Min OD: 38mm •Gauge restrictions 3-8 Described
23 Process Blow out •Currently 14.5m •OD: 38 – 168.3mm •Capacity: 62 tubes/h Described
24 Process EC tester •OD: 60.3 – 200.5mm •Full body skin •One tube a time •Man: 1 Described
Files
Parameters
Rules
Record: 1 of 12

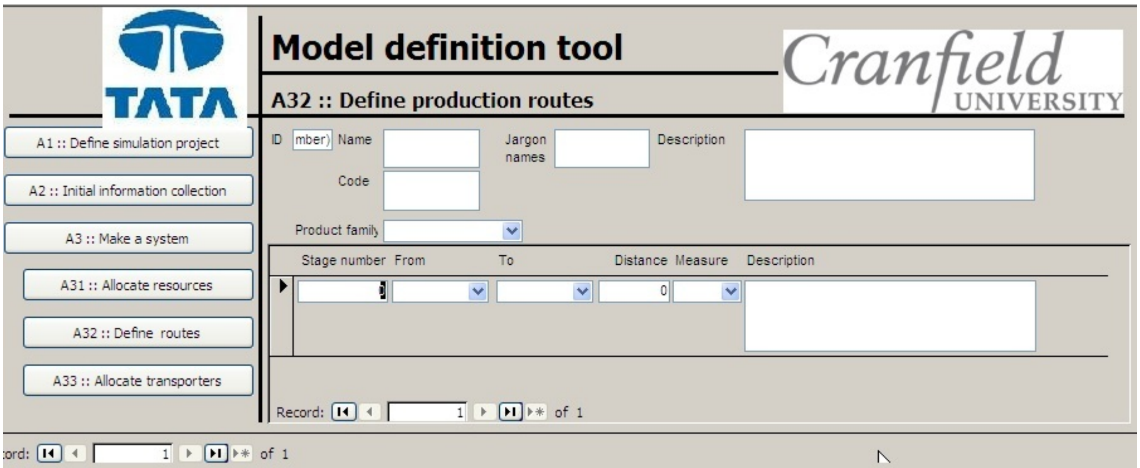

TATA
Model definition tool
Cranfield UNIVERSITY
A22 :: Define product families
A1 :: Define simulation project
A2 :: Initial information collection
A21 :: Define products
A22 :: Define process
A23 :: Define stores
A24 :: Define transporters
A25 :: Define resources
A3 :: Make a system
ID Element type Name Code Jargon names Description State Preview Report
31 Product Product family 1 Loading table 1, Straightener, Blow out, PE, EC, Visual inspection, packing Described
32 Product product famlity 2 loading table 2, visual inspection, packing Described
33 Product product family 3 loading table 1, blow out, PE, visual inspection, packing Described
34 Product product family 4 loading table 1, streightener, PE, visual inspection, packing Described
35 Product product family 5 loading table 1, streightener, PE, EC, visual inspection, packing Described
36 Product product family 6 loading table 1, streightener, blowout, PE, EC< hydro tester, Described
Files
Parameters
Rules
Record: 1 of 10

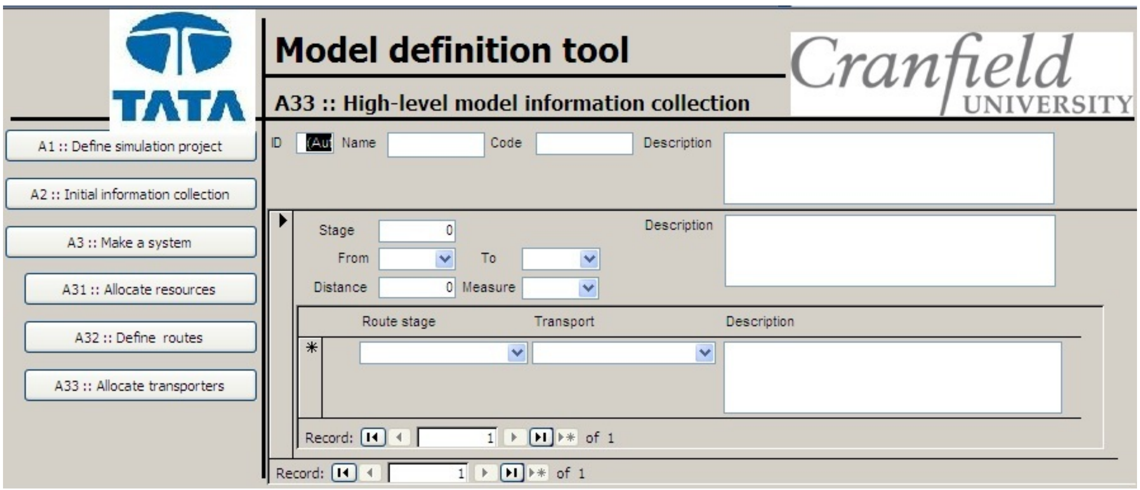

Model definition tool
Cranfield UNIVERSITY
TATA
A23 :: Define stores
A1 :: Define simulation project
A2 :: Initial information collection
A21 :: Define process
A22 :: Define products
A23 :: Define stores
A24 :: Define transporters
A25 :: Define resources
A3 :: Make a system
ID Element type Name Code Jargon names Description State
Preview Report
41 Store Store
•Store for ongoing materials is 600 t big for loose tubes, and 400 t big for packed
Described
Files
Parameters
Rules
Store


Model definition tool
Cranfield UNIVERSITY
TATA
A24 :: Define transporters
A1 :: Define simulation project
A2 :: Initial information collection
A21 :: Define process
A22 :: Define products
A23 :: Define stores
A24 :: Define transporters
A25 :: Define resources
A3 :: Make a system
ID Element type Name Code Jargon names Description State
Preview Report
42 Transport Crane
•Long travel: 137 m/min
•Cross travel: 69.9 m/min
Described
43 Transport Road transportation system RTS RTS
•2 * standalone E-type trailers available
•If these trailers are available, than there
Not described
44 Transport Conveyor
Conveyors are not worth modelling, however, it still takes 5 seconds to
Not described
Files
Parameters
Rules


Model definition tool
Cranfield UNIVERSITY
TATA
A25 :: Define resources
A1 :: Define simulation project
A2 :: Initial information collection
A21 :: Define process
A22 :: Define products
A23 :: Define stores
A24 :: Define transporters
A25 :: Define resources
A3 :: Make a system
ID Name Code Jargon names Cost per unit Measure Description State
Preview Report
Man
0
Resources having major affect on production cost are people and fuel. In
Not described
Files
Parameters


Model definition tool
A31 :: Allocate resources
A1 :: Define simulation project
A2 :: Initial information collection
A3 :: Make a system
A31 :: Allocate resources
A32 :: Define routes
A33 :: Allocate transporters
ID 4 Name Transport Description
ID Name Road transporta Jargon names RTS Description
•2 * standalone E-type trailers available
•If these trailers are available, than there are no problems with transportation
•It takes 6-8 minutes to unload 2 tone
Code RTS
Element Resource Number of units Description
RTS 0
Record: 1 of 1
Record: 2 of 3
cord: 4 of 4


Model definition tool
A32 :: Define production routes
A1 :: Define simulation project
A2 :: Initial information collection
A3 :: Make a system
A31 :: Allocate resources
A32 :: Define routes
A33 :: Allocate transporters
ID mber) Name Jargon names Description
Code
Product family
Stage number From To Distance Measure Description
0
Record: 1 of 1
cord: 1 of 1


Model definition tool
A33 :: High-level model information collection
A1 :: Define simulation project
A2 :: Initial information collection
A3 :: Make a system
A31 :: Allocate resources
A32 :: Define routes
A33 :: Allocate transporters
ID Name Code Description
Stage 0 Description
From To
Distance 0 Measure
Route stage Transport Description
Record: 1 of 1
Record: 1 of 1